Dark Matter Characterization at the LHC

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arXiv:0907.3142, arXiv:0907. 3146, arXiv:1003.0899, and arXiv:1010.1???
with K. Agashe, D. Kim, M. Toharia and L. Zhu

Motivation and Goals

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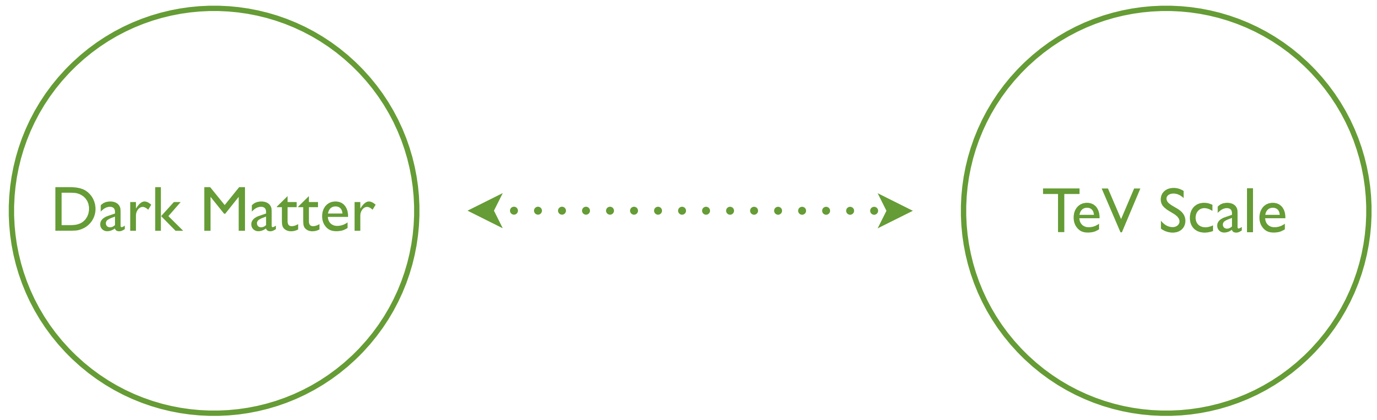

- Connection with DM and TeV scale

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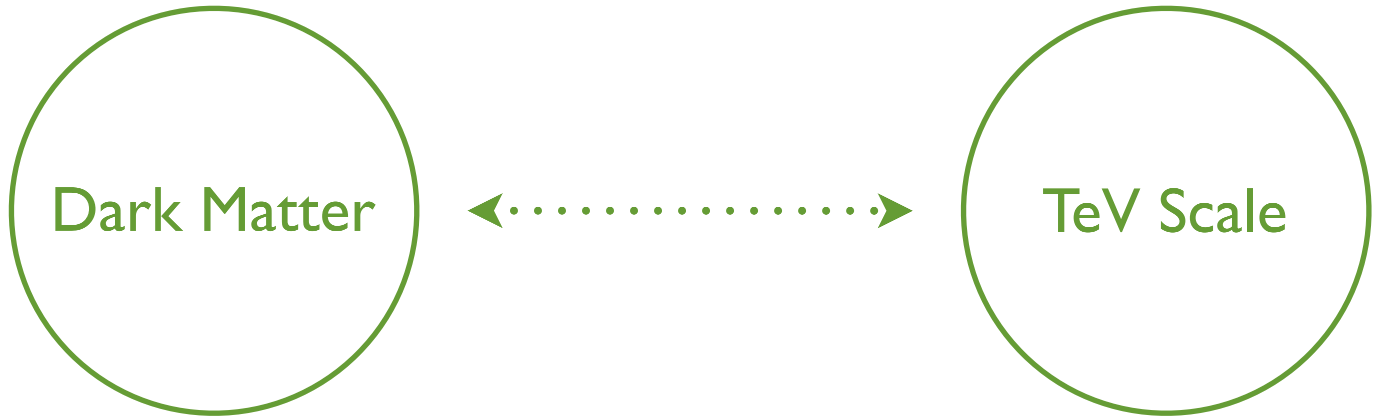

- Connection with DM and TeV scale
  - Relic abundance for thermal DM

$$h^2\,\Omega_{\mathrm{DM}} \simeq \frac{0.1\ \mathrm{pb}\cdot c}{\langle\sigma v\rangle} \qquad\qquad \langle\sigma v\rangle \simeq \frac{g^4}{8\pi}\frac{1}{M^2}$$

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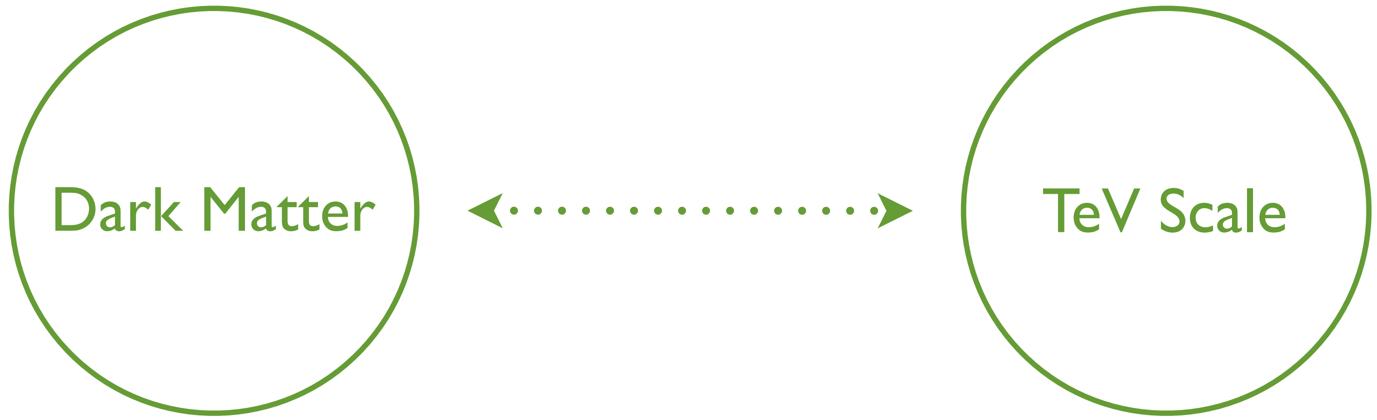

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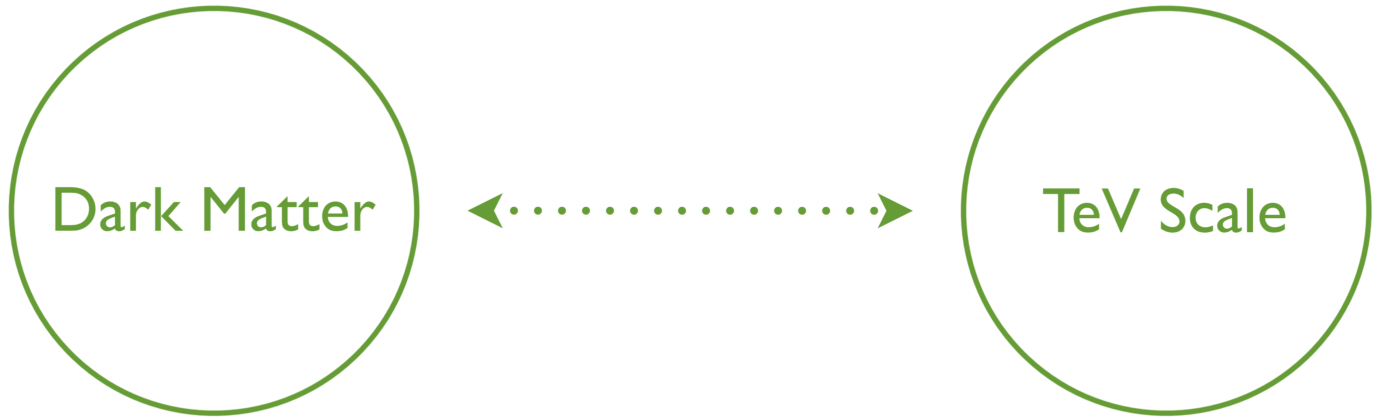

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  - Hierarchy Problem: TeV scale models often have O(100) GeV DM.
- LHC set to explore TeV scale!

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- Today: Focus on distinguishing models with Z2 (parity) stabilization symmetries from models with other stabilization symmetries.

How to do this...

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- Ultimately searching for different decay topologies

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  - Main point: Different stabilization symmetries generate different decay topologies.

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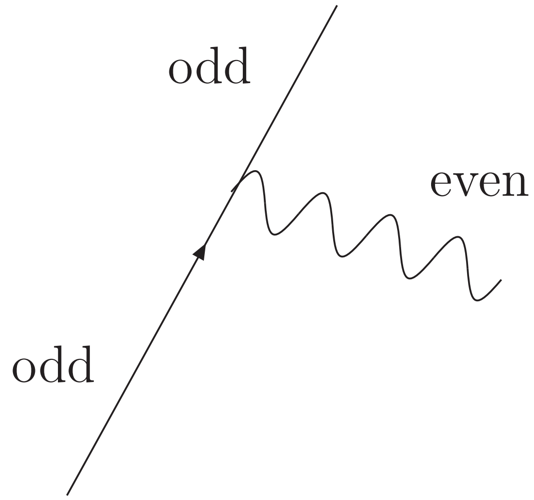

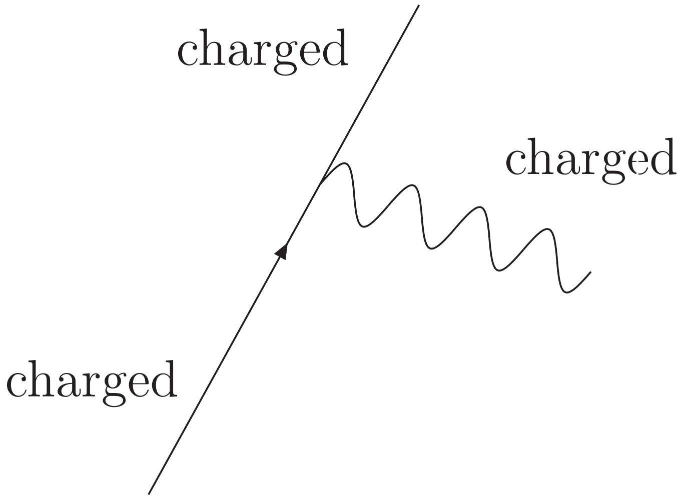

How to do this...

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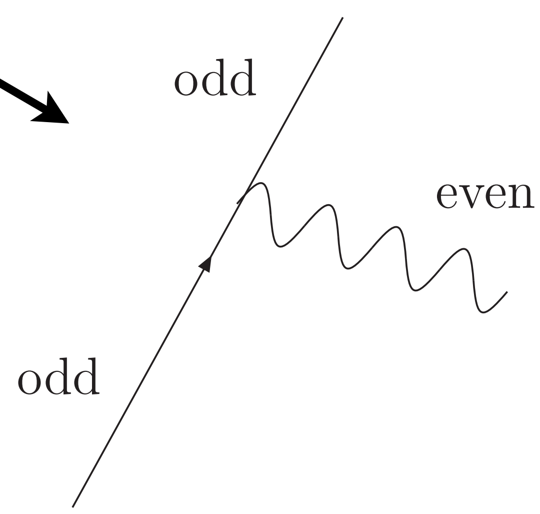
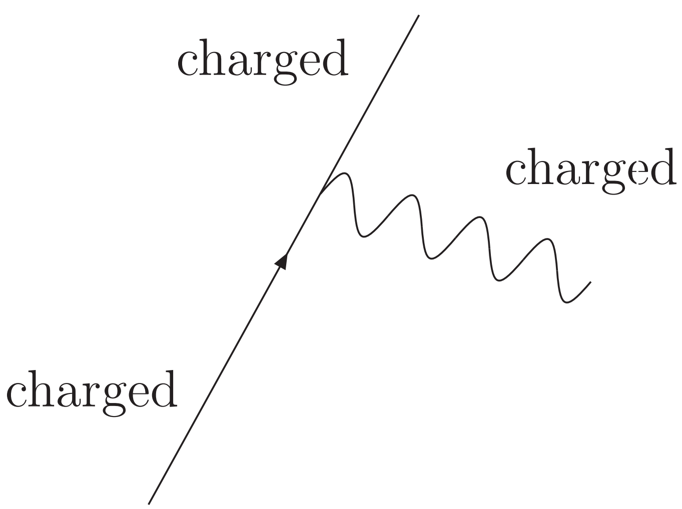
only parity stabilized models





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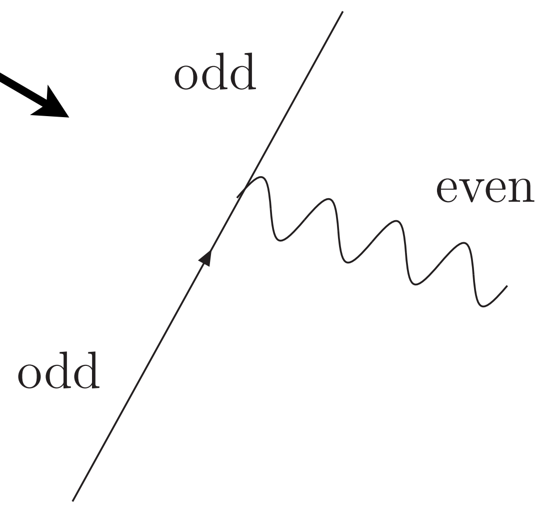
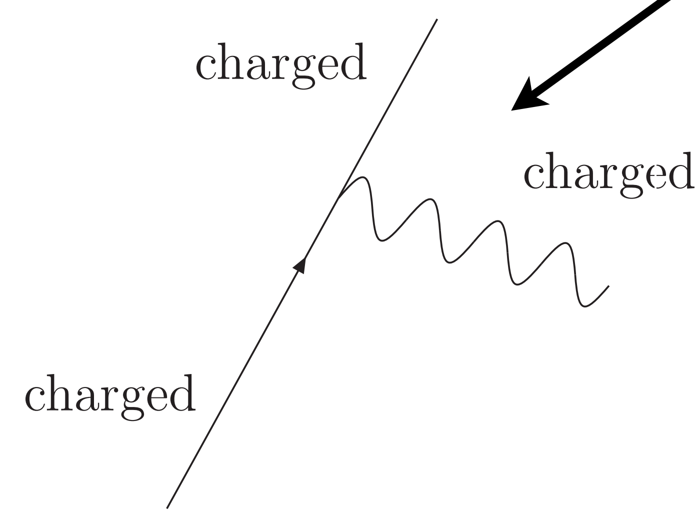


never for parity stabilized models



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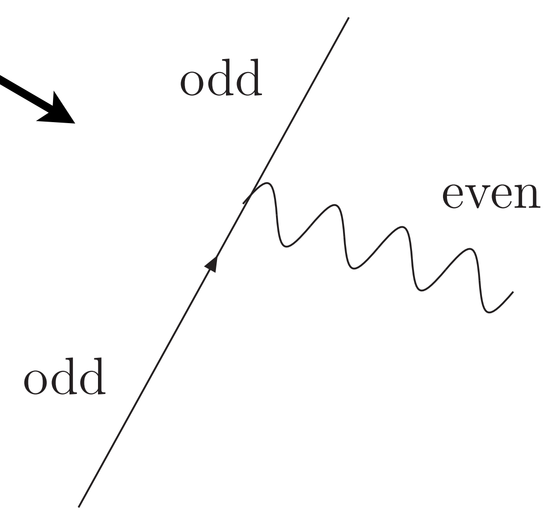

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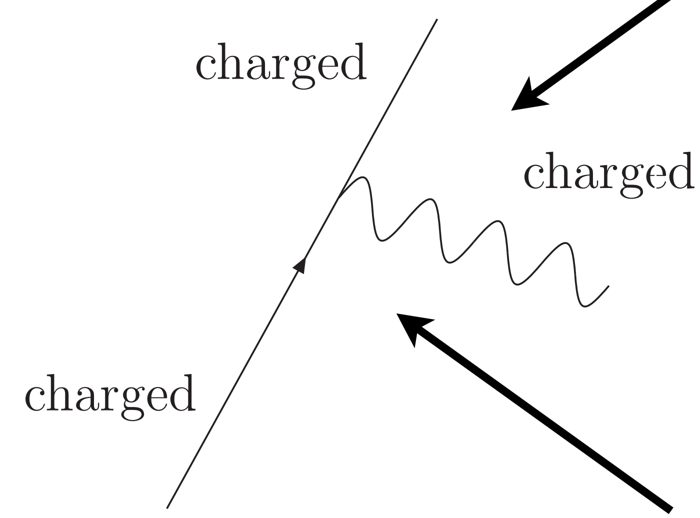

e.g., *Z3*, *Z2 x Z2*, ...

How to do this...

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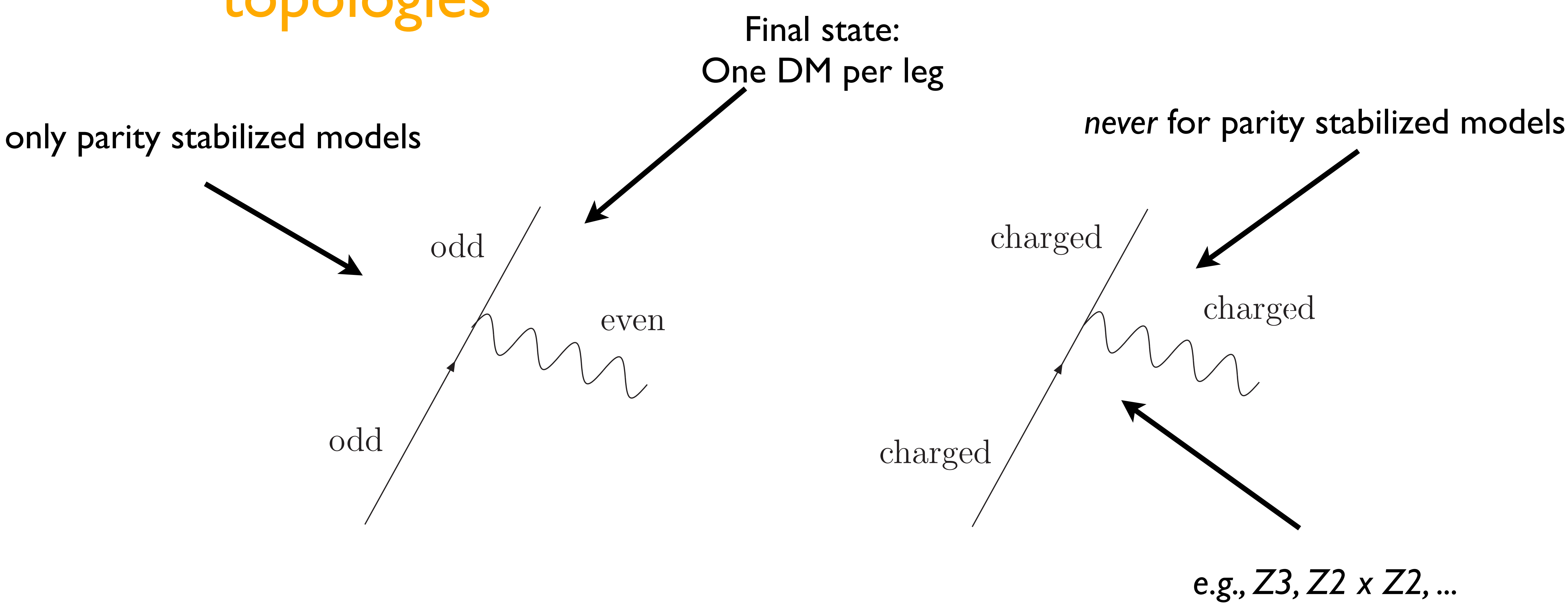

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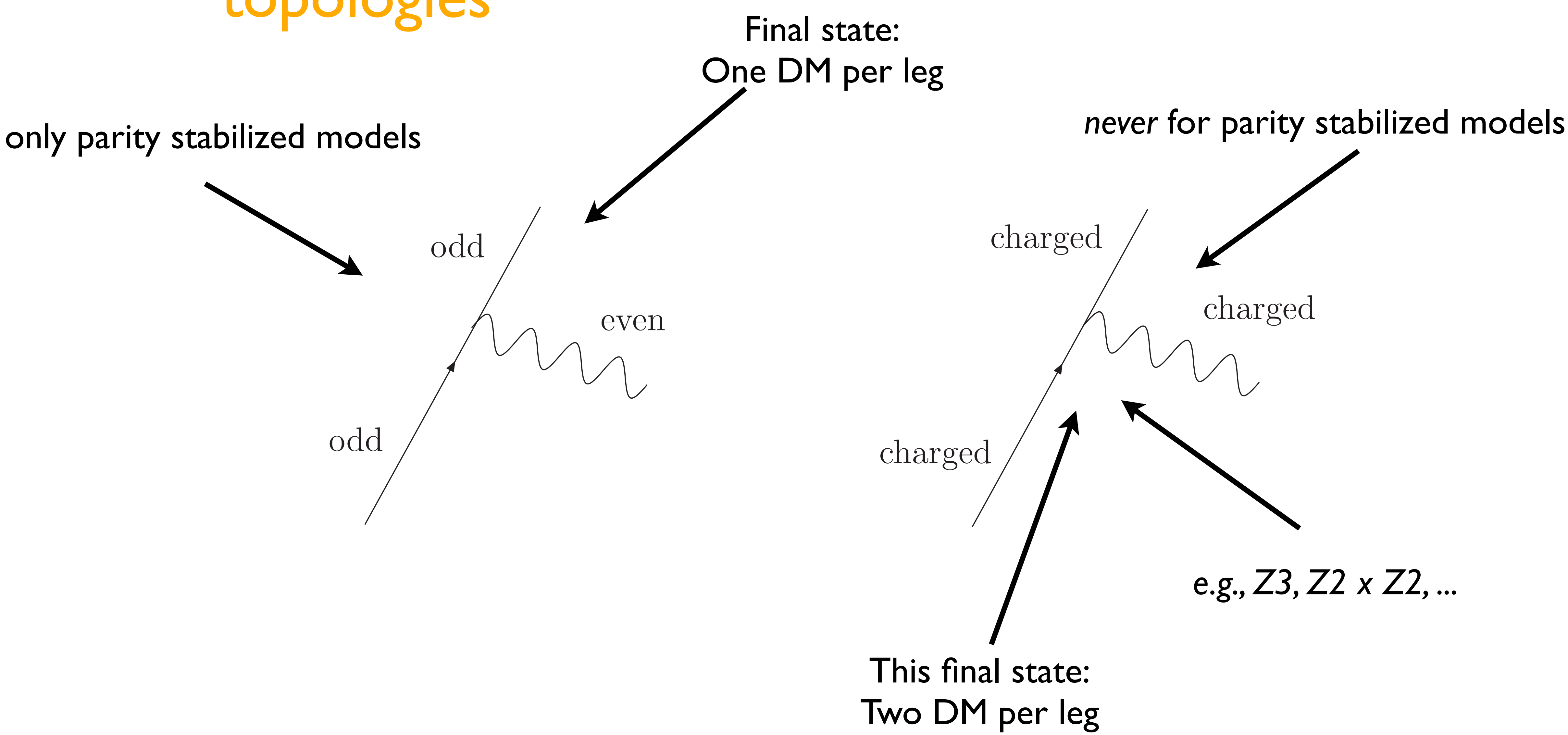


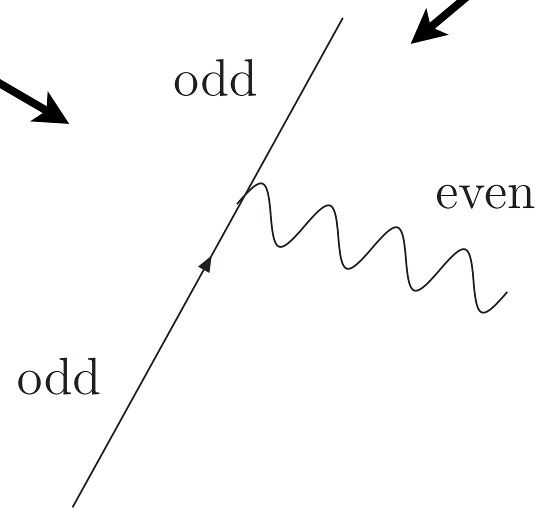
How to do this...

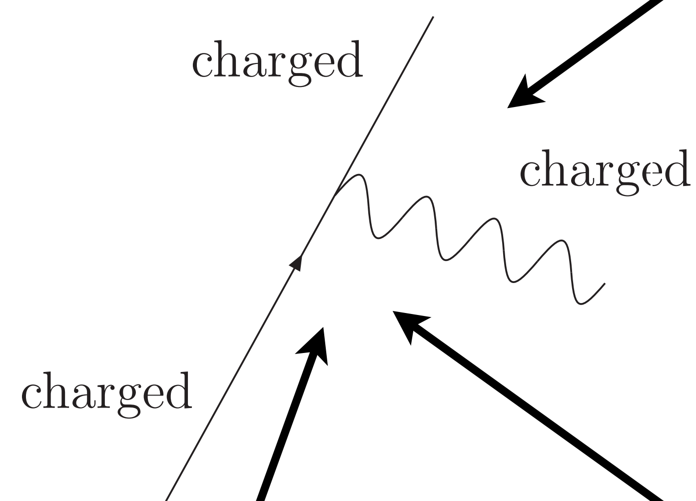
- Ultimately searching for different decay topologies

Final state:
One DM per leg

only parity stabilized models

never for parity stabilized models





e.g., *Z3, Z2 x Z2, ...*

This final state:
Two DM per leg

- Searching for scenarios w/ one or two DM per leg.

The Plan

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- Unique Decay Topology and Reconstruction (10 Minutes)

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- Topologies and MT2 Reconstruction (10 Minutes)

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- Signatures with Metastable Particles
  (7 Minutes)

The Plan

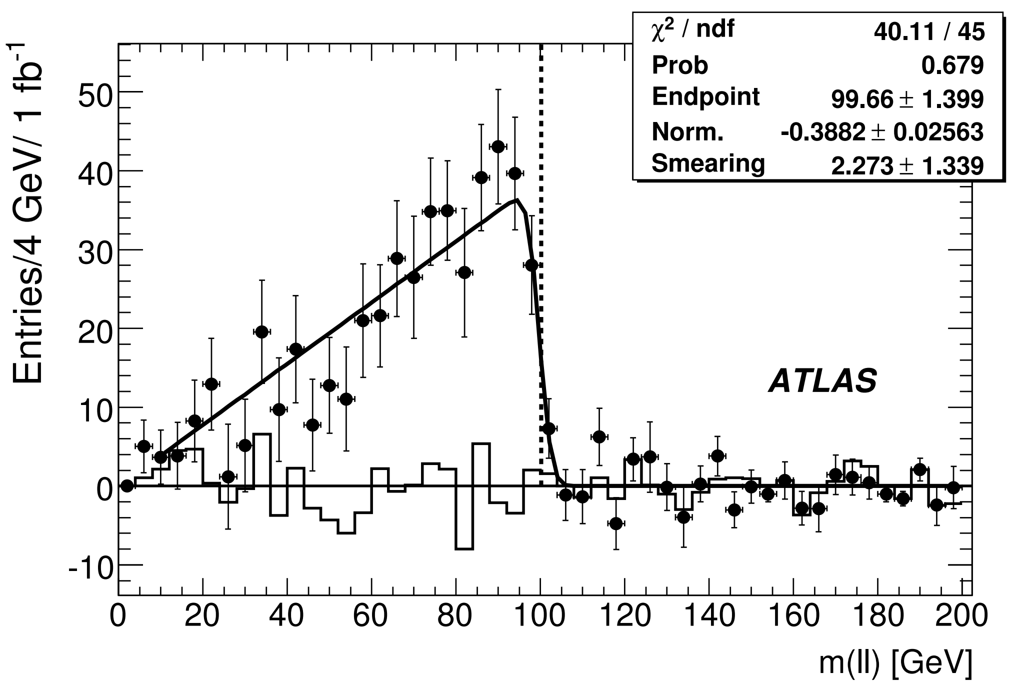
- Unique Decay Topology and Reconstruction (10 Minutes)
- Topologies and MT2 Reconstruction (10 Minutes)
- Signatures with Metastable Particles (7 Minutes)
- Future work/Conclusions

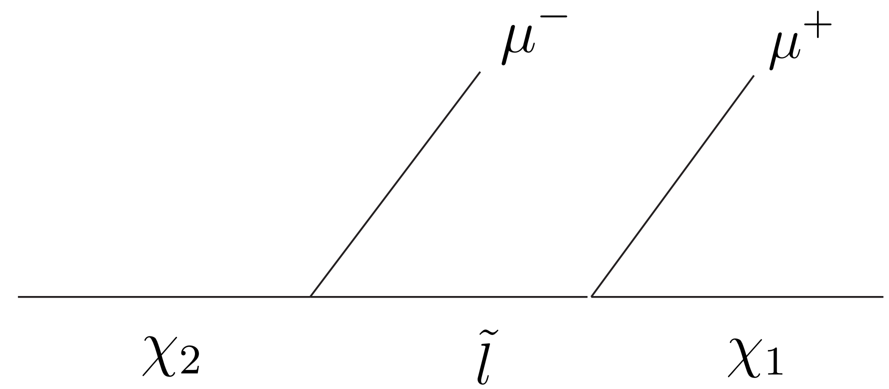
Part I: Unique Decay Topologies and Reconstruction

Decays for Parity Models

(a one slide review)

- Standard searches at LHC involves kinematic endpoints.



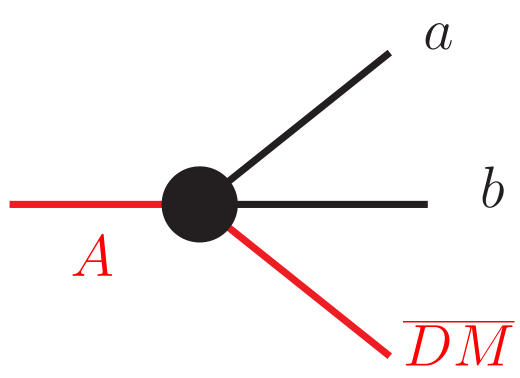


$$m_{\ell\ell}^{\text{edge}} = m_{\tilde{\chi}_2^0}\sqrt{1-\left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2}\sqrt{1-\left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2}$$

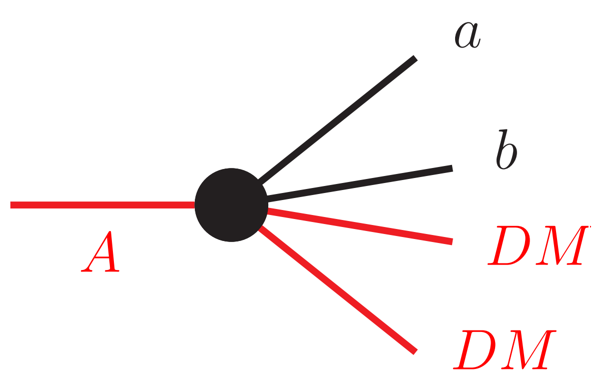
m_{χ_2} = 218.6 GeV, $m_{\tilde{l}}$ = 230.45, m_{χ_1} = 117.91

Non-Parity Decay Chains

- "Non-parity" models have one or more DM candidates per decay chain!



$\mathcal{Z}_2$ and non-parity diagrams



A correction for "non-parity" diagrams

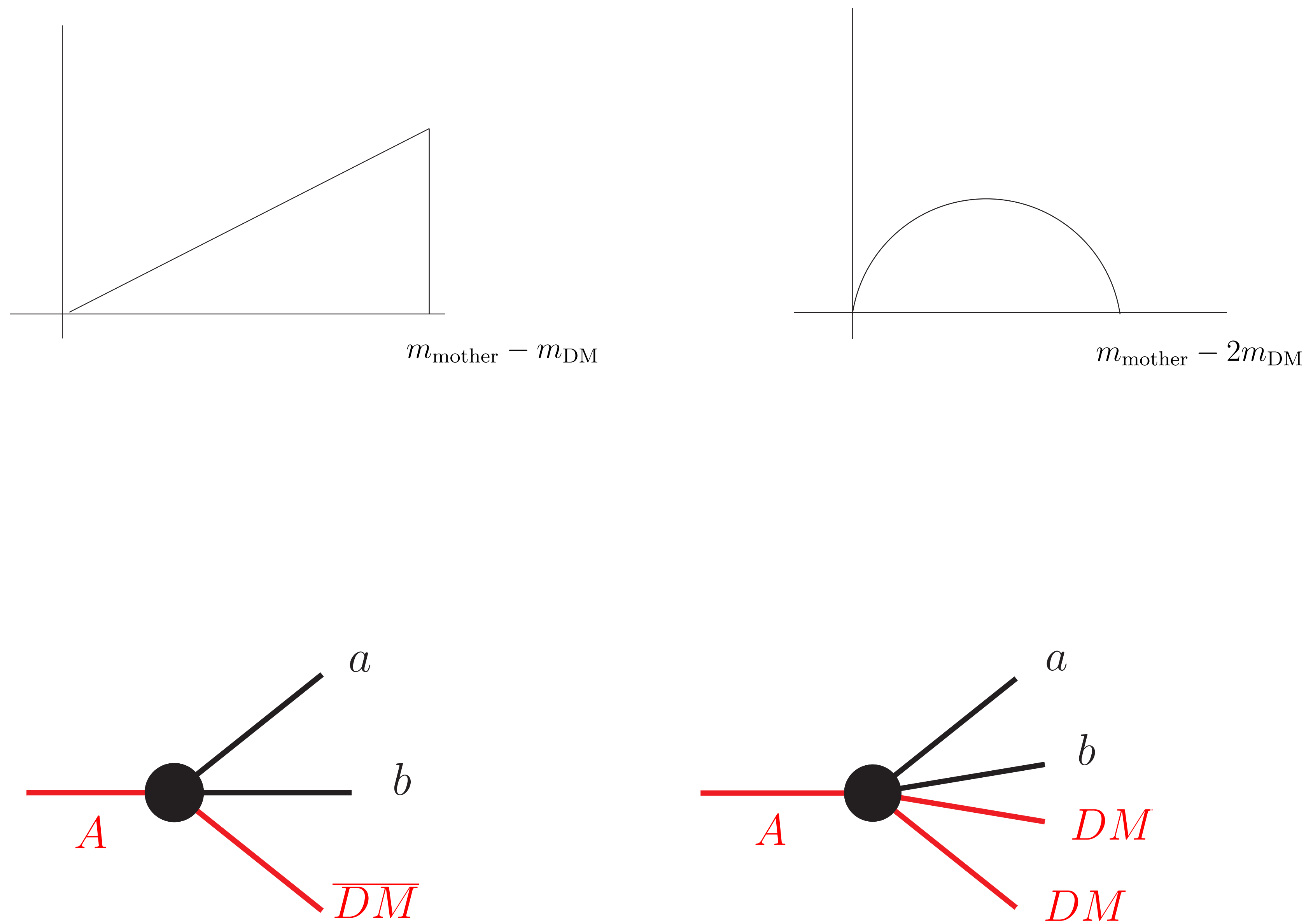
Non-Parity Decay Chains

- "Non-parity" models have one or more DM candidates per decay chain!

- Generates a double kinematic edge.
- Direct calculation of DM mass.

Off-Shell Edges

- Off-shell cartoon:



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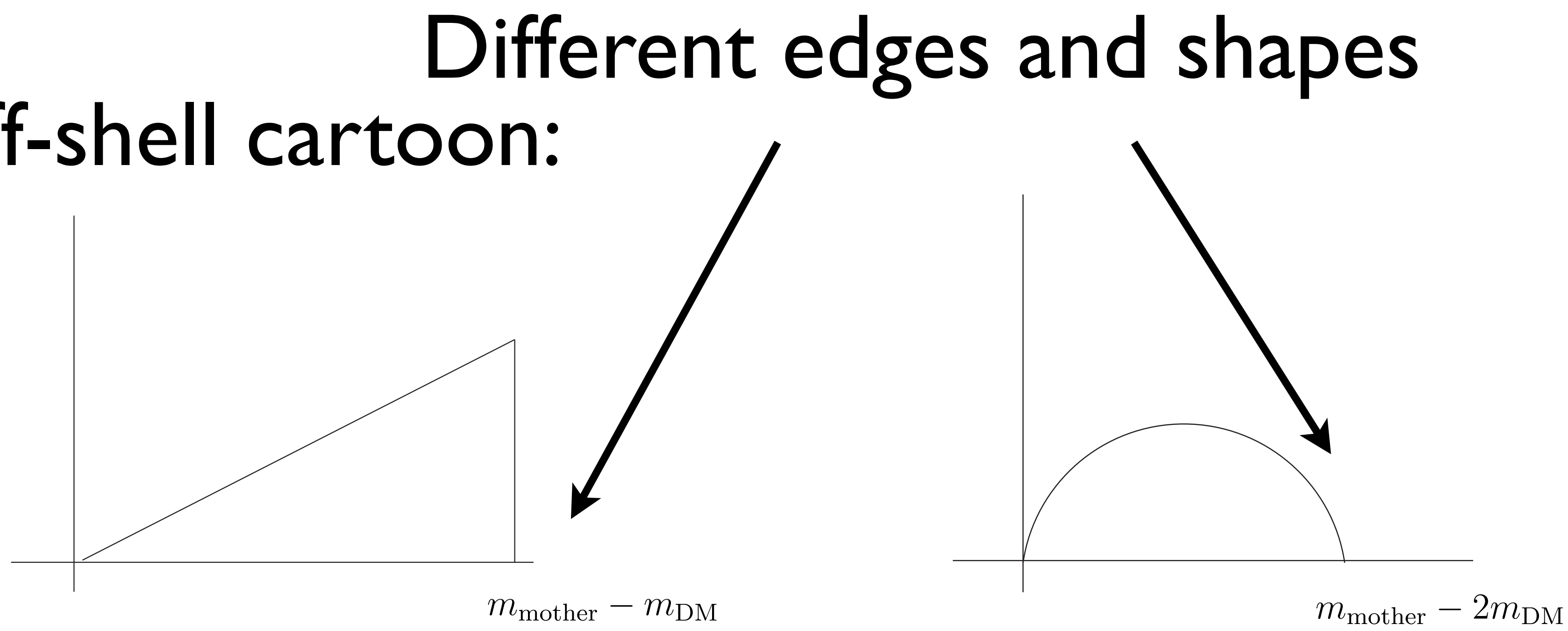
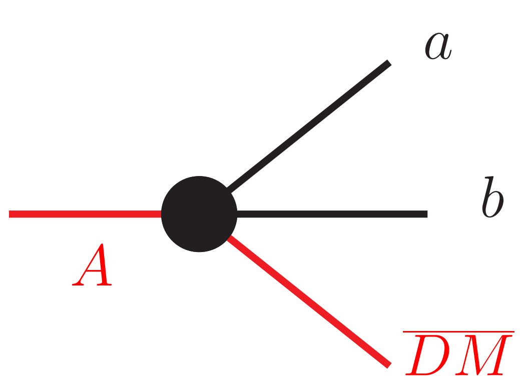
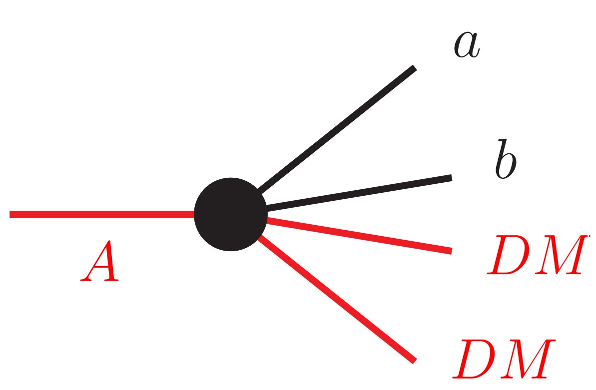


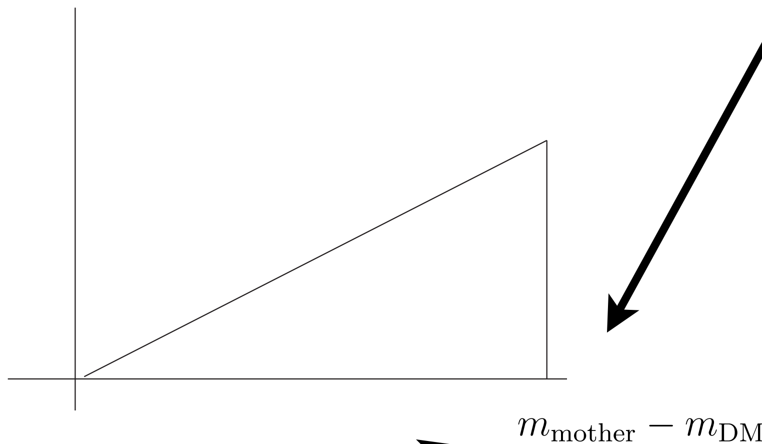


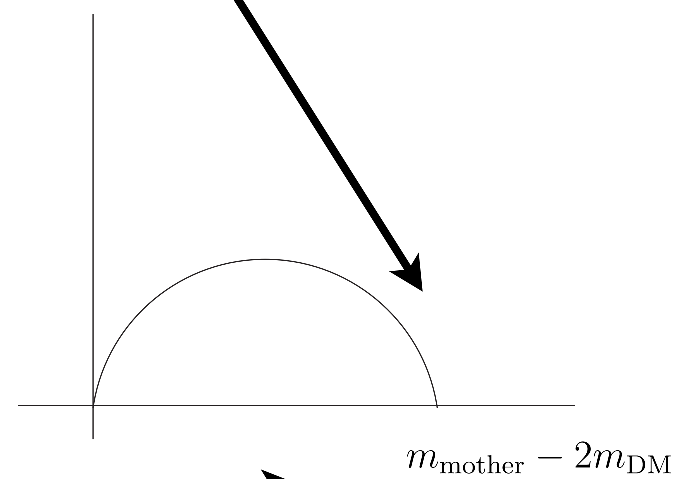


Off-Shell Edges

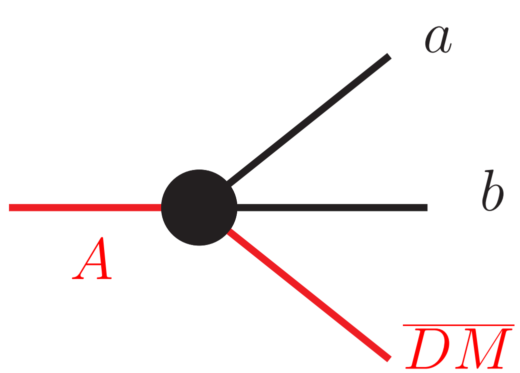
Different edges and shapes

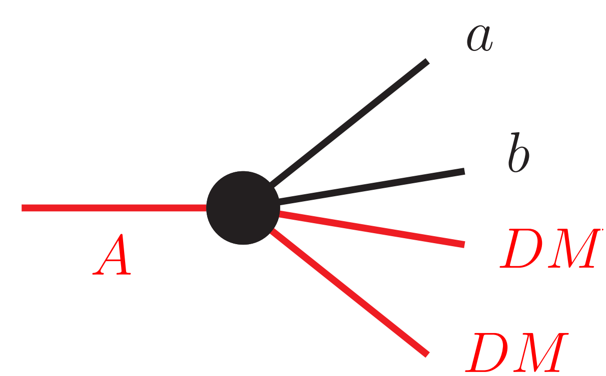
- Off-shell cartoon:





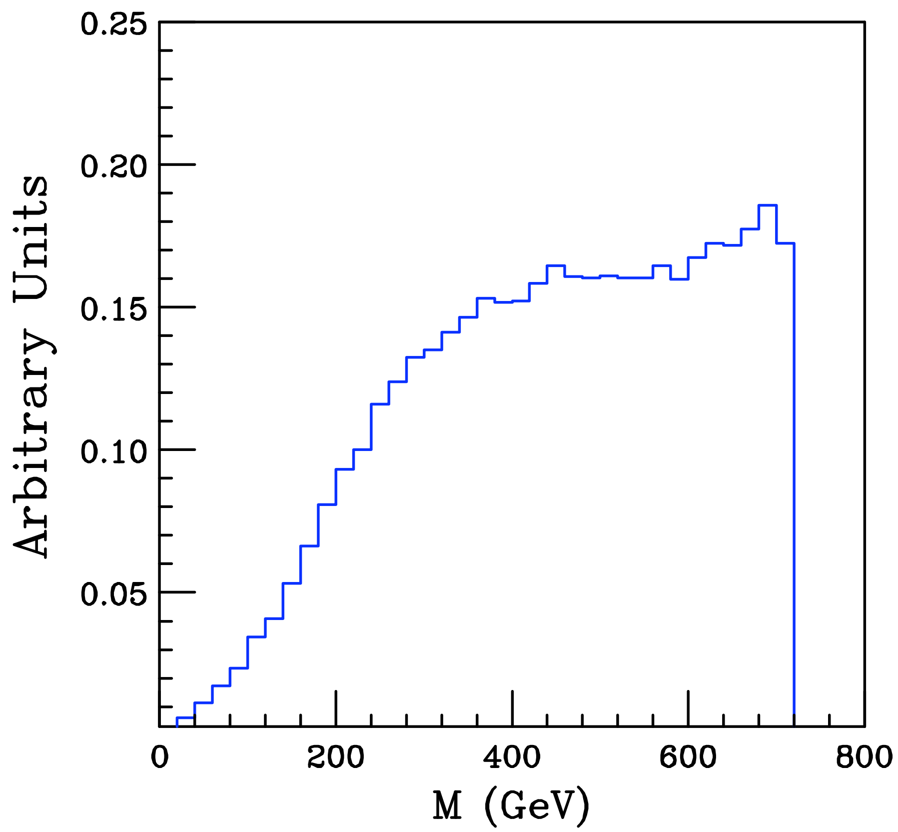
Two equations
two unknowns

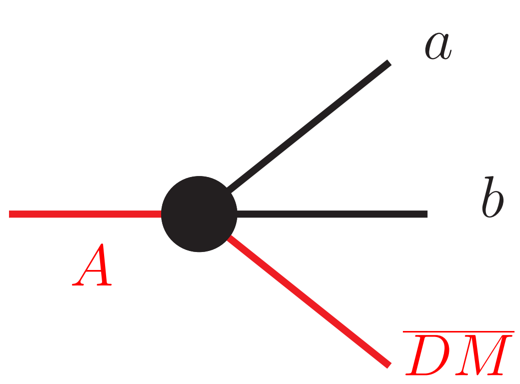


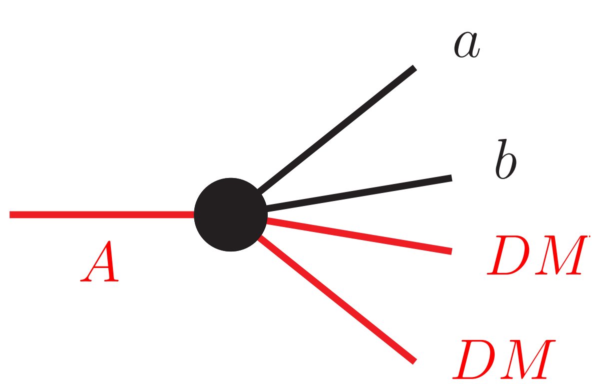


Off-Shell Edges

Cross sections summed







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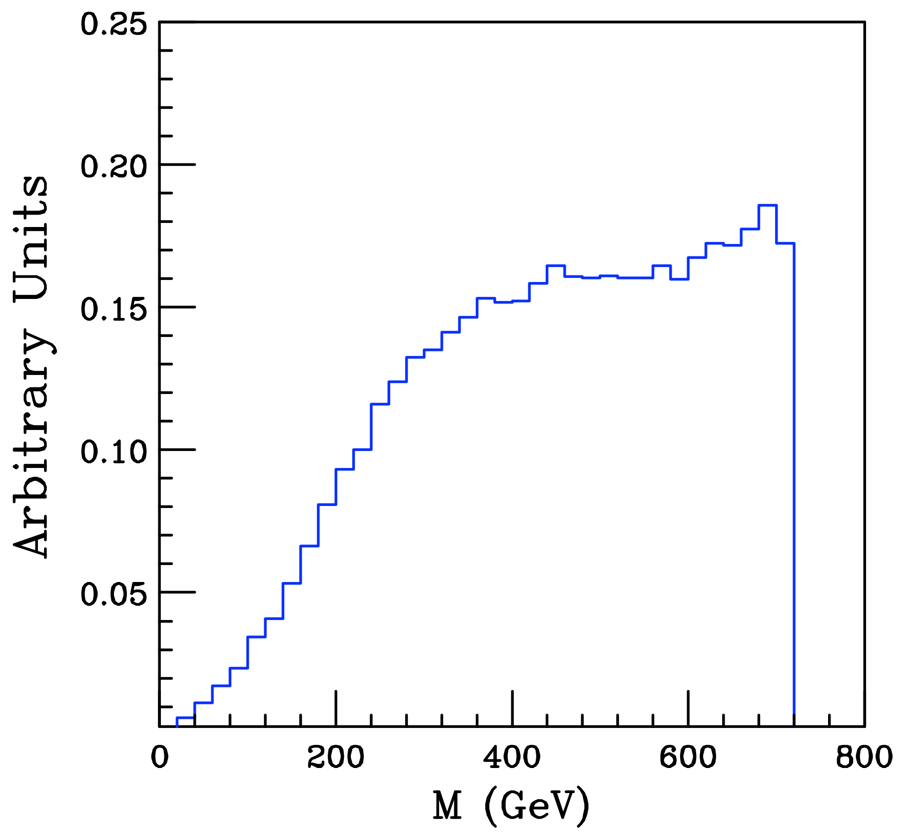

- 820 GeV mother and 100 GeV DM, vector-like couplings.

Off-Shell Edges

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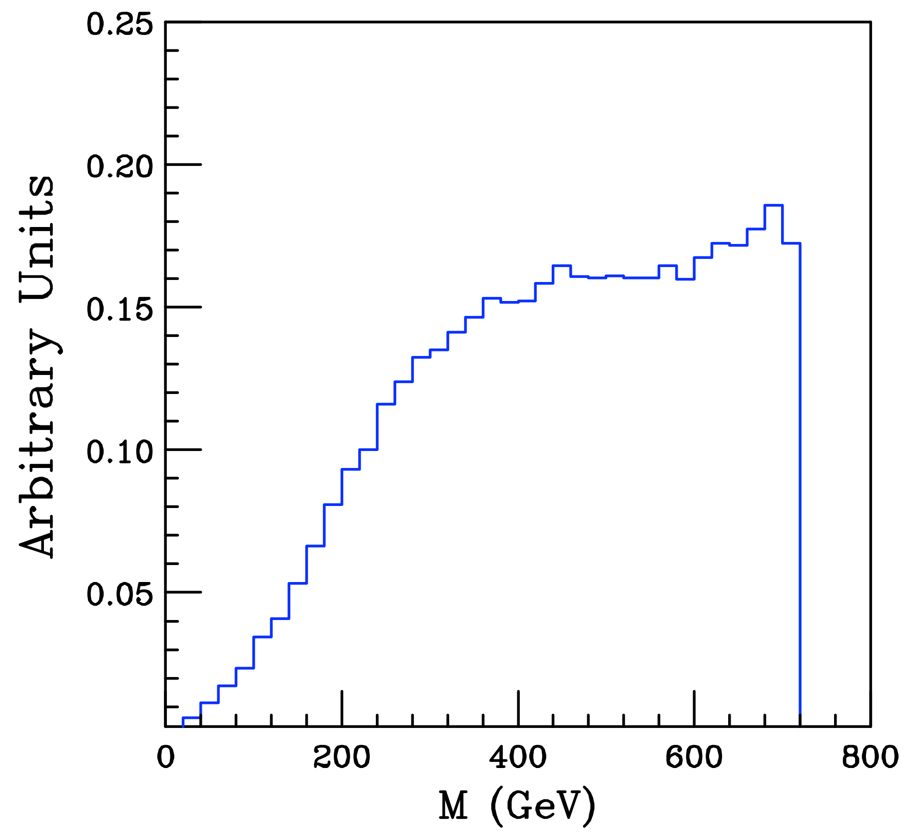
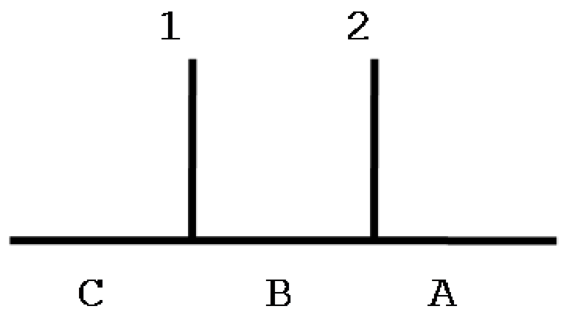


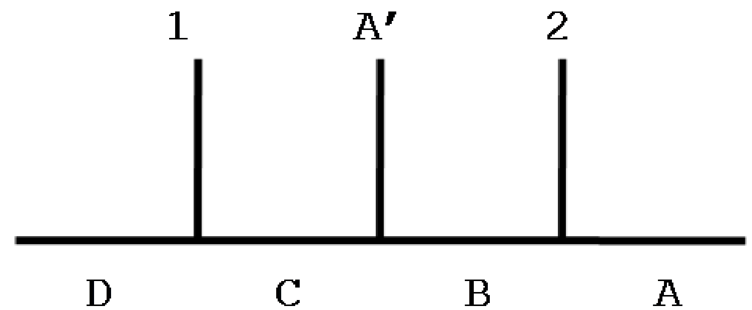
- 820 GeV mother and 100 GeV DM, vector-like couplings.
- Second endpoint at about 620 GeV.

On-Shell Considerations

- Any unique features underneath the effective coupling?

On-Shell Considerations

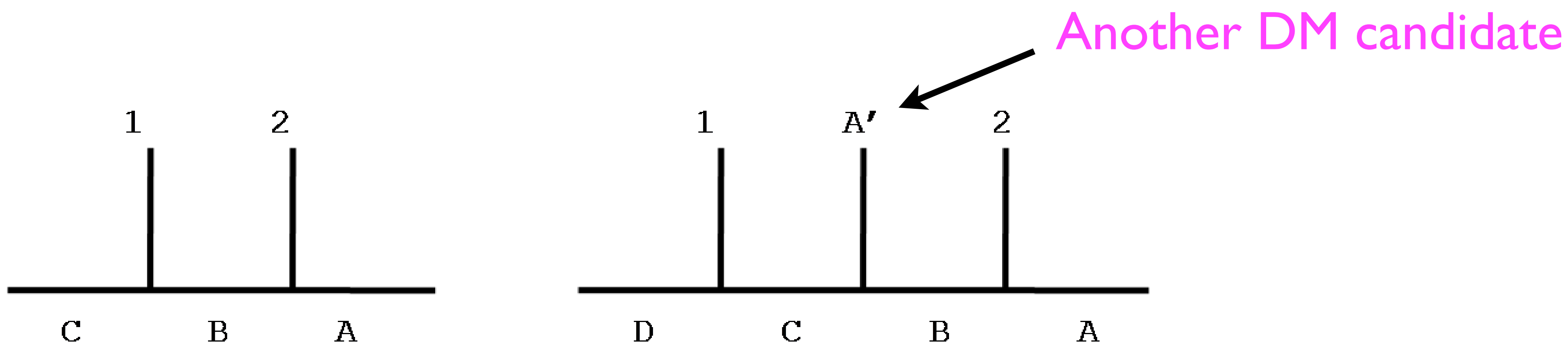




- Consider the decay with the mass hierarchy:

$$m_D > m_C > m_B > m_A$$

On-Shell Considerations



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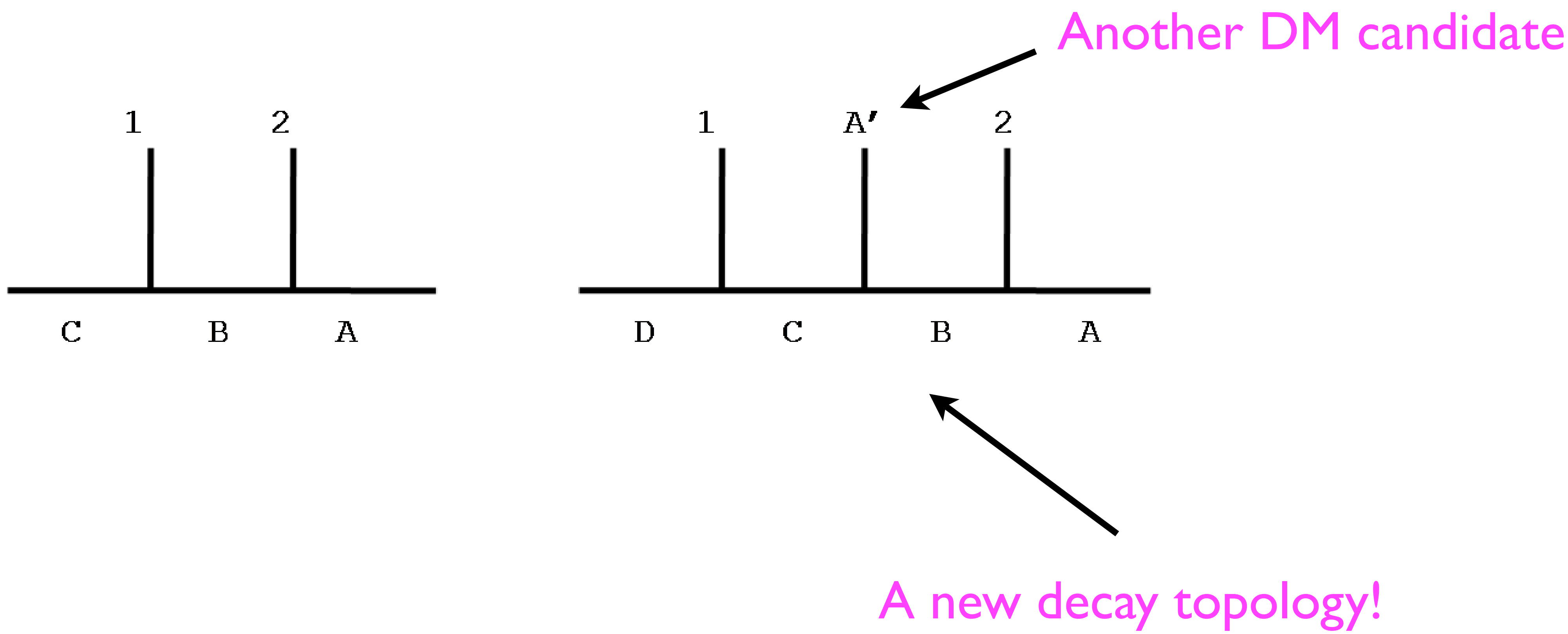

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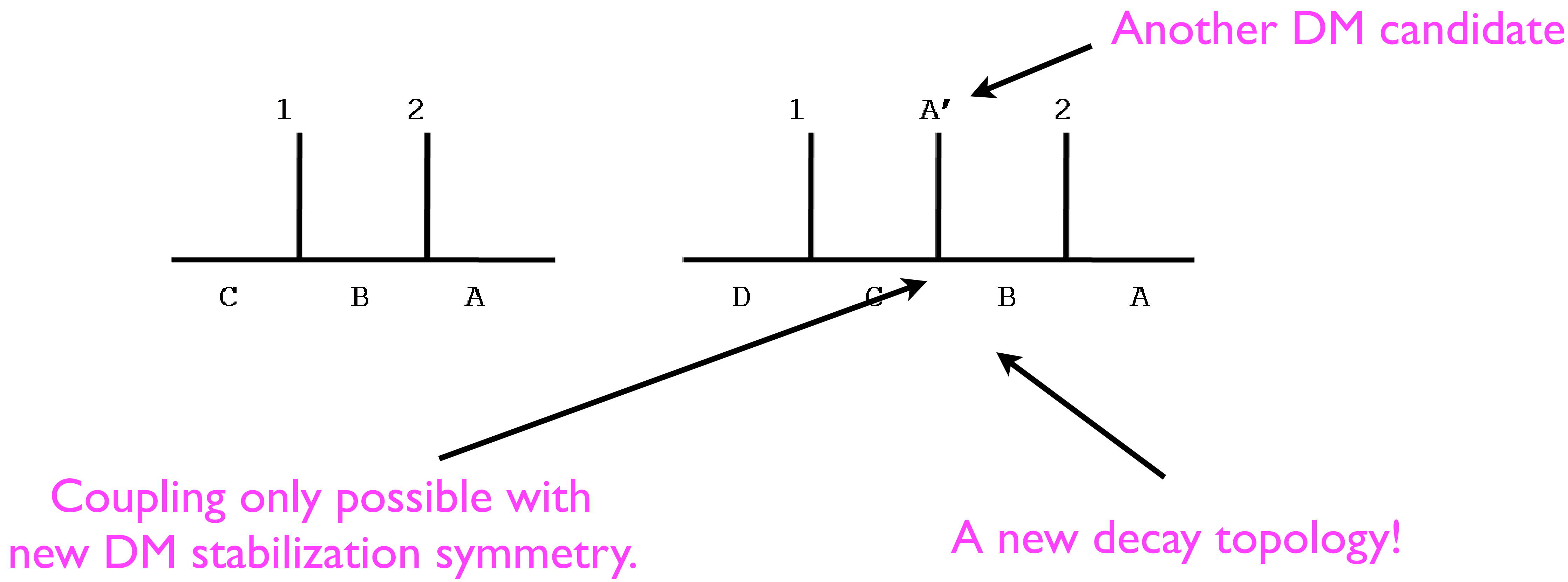


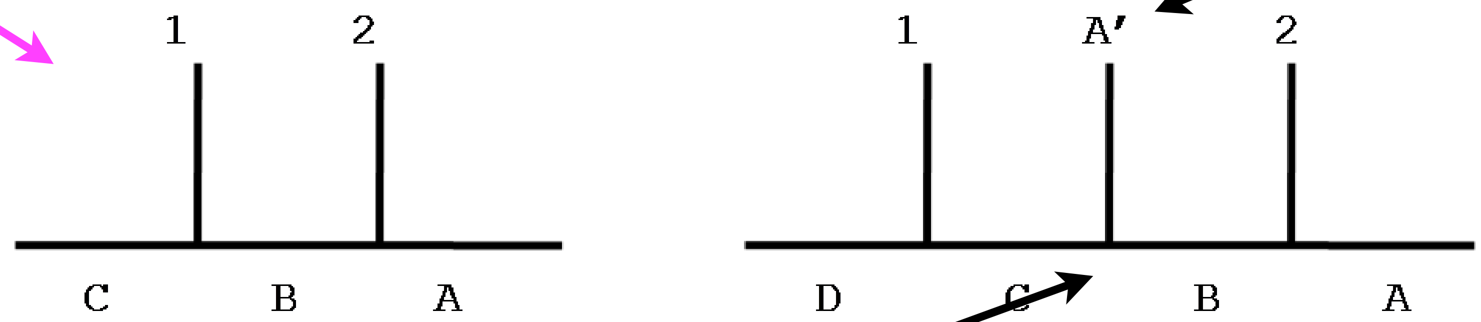
- Consider the decay with the mass hierarchy:

$$m_D > m_C > m_B > m_A$$

On-Shell Considerations

Often dominant: Care required to see "non-parity" signal.

Another DM candidate



Coupling only possible with new DM stabilization symmetry.

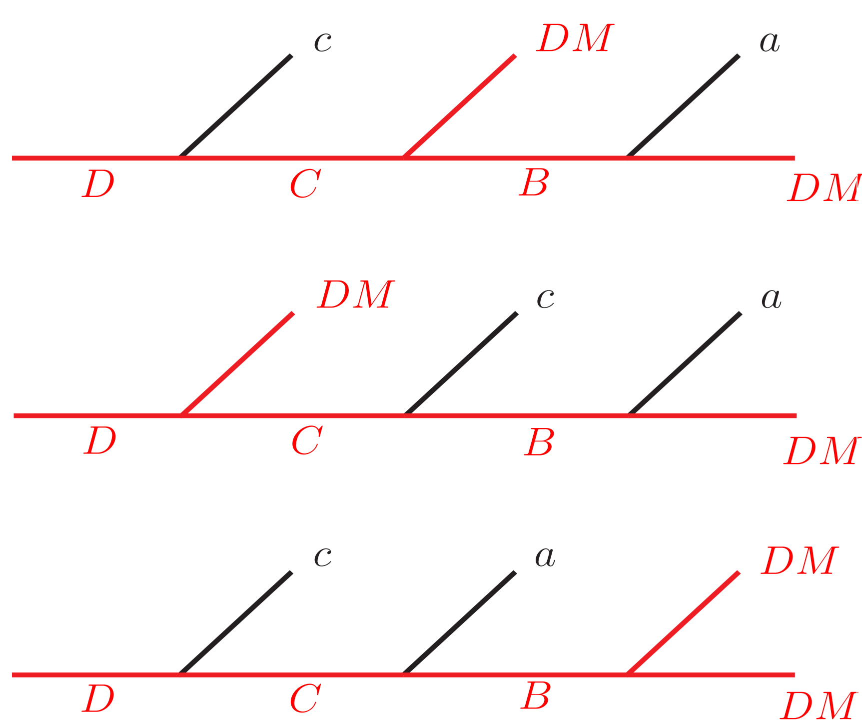
A new decay topology!

- Consider the decay with the mass hierarchy:

$$m_D > m_C > m_B > m_A$$

Additional Possible Topologies

- Many unique topologies:



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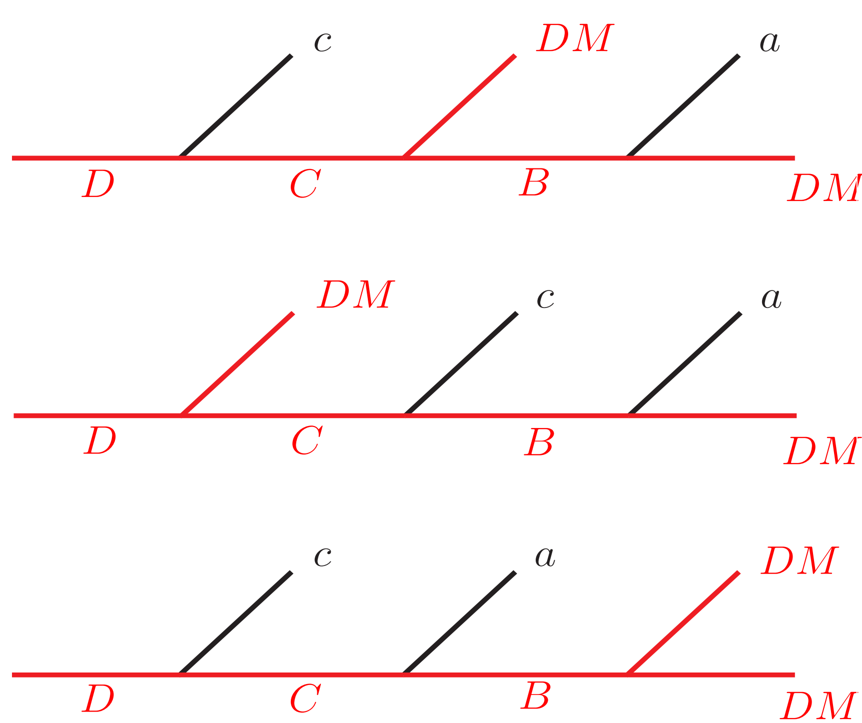

Focus on this topology first.

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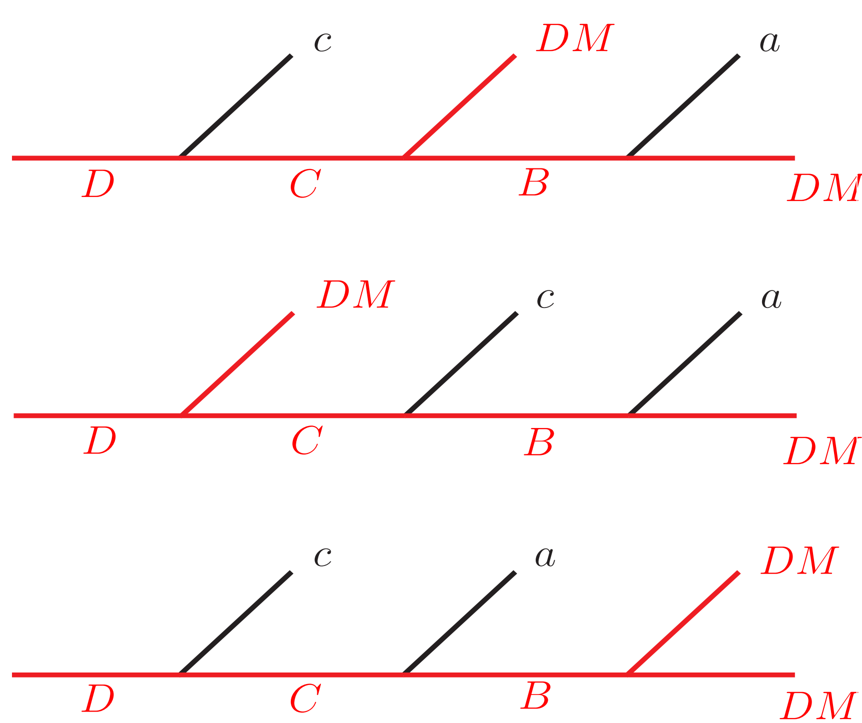
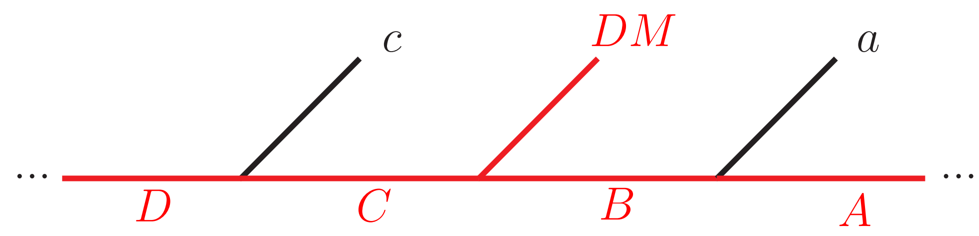
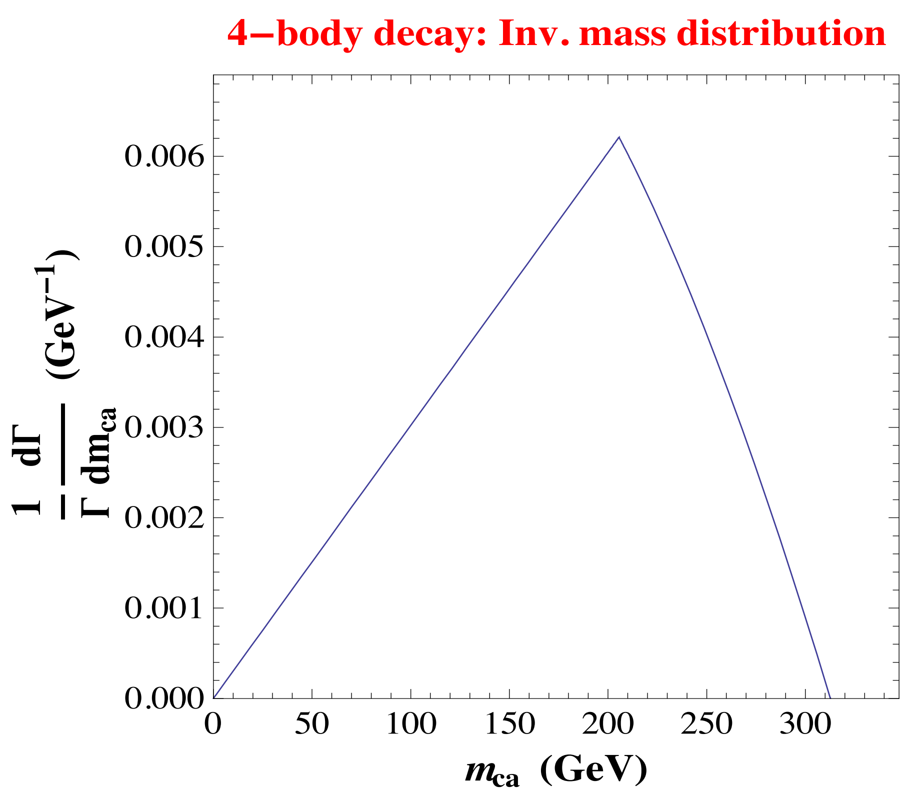


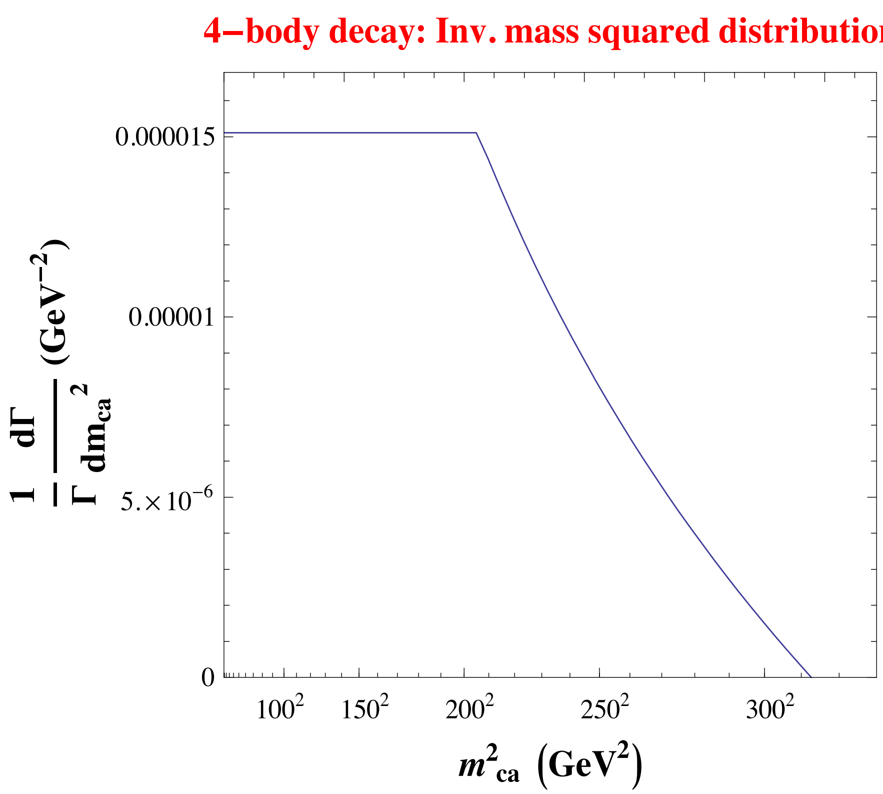
Focus on this topology first.

Distinguish these topologies with MT2 momentarily.

Our Signal







A, B, C and D have masses of 200, 400, 700 and 800 GeV

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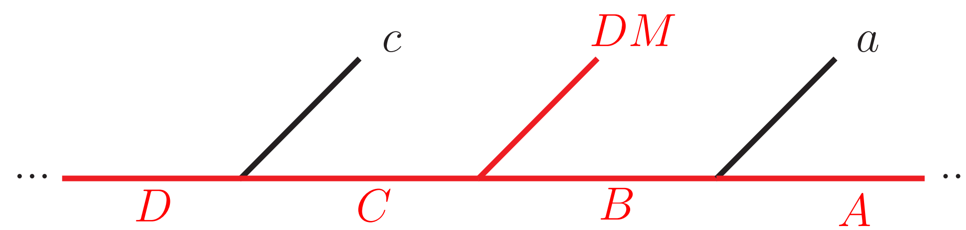
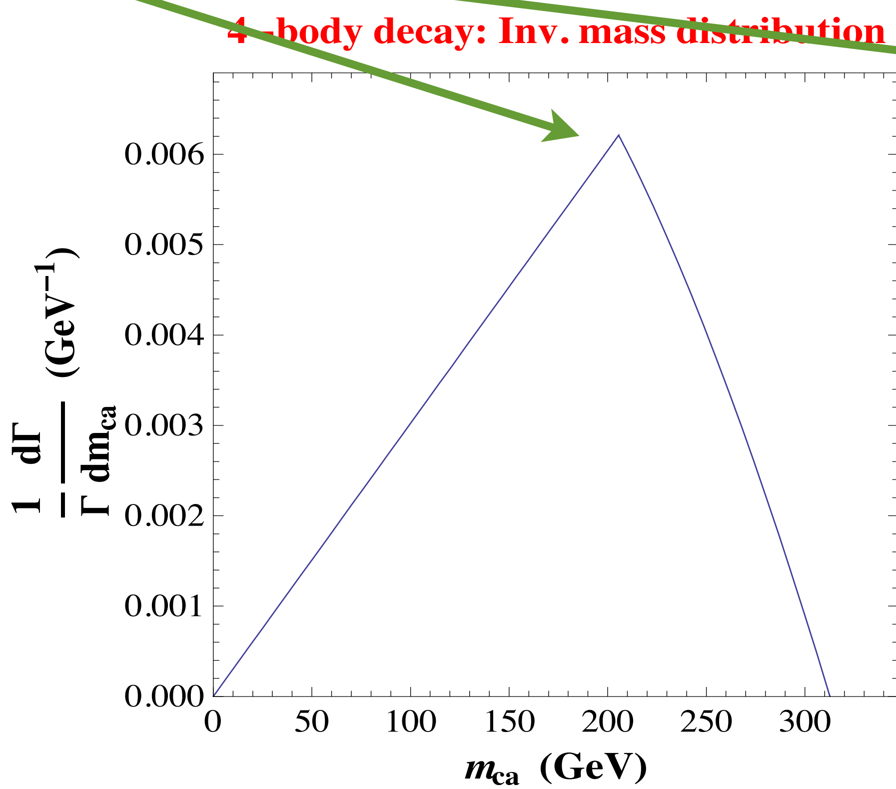
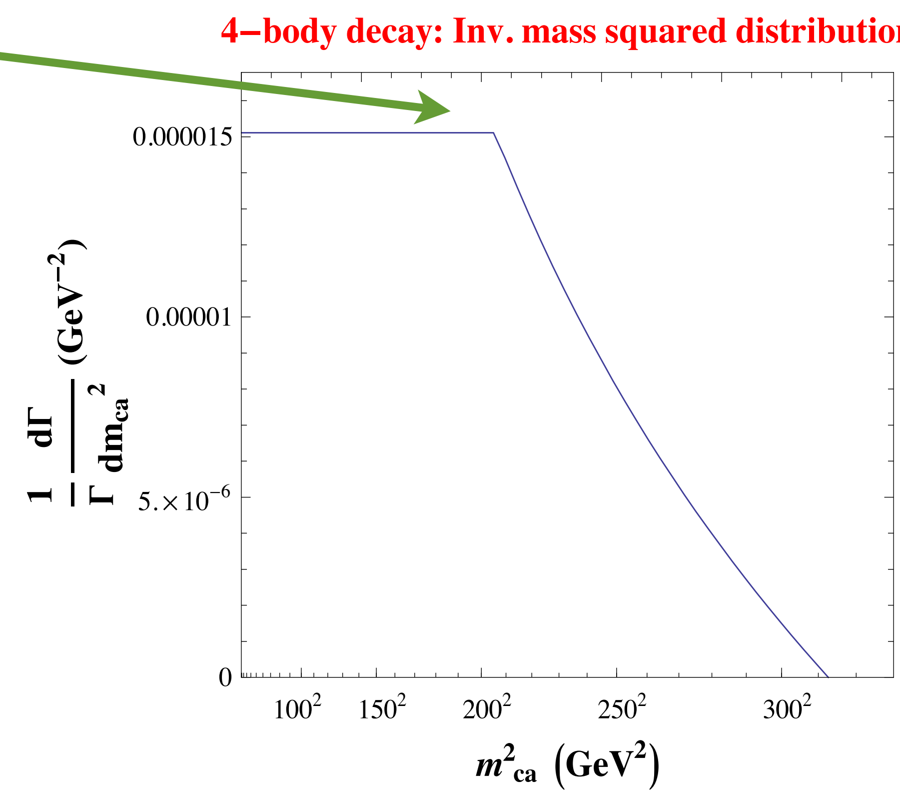


Discontinuity in the cross section.





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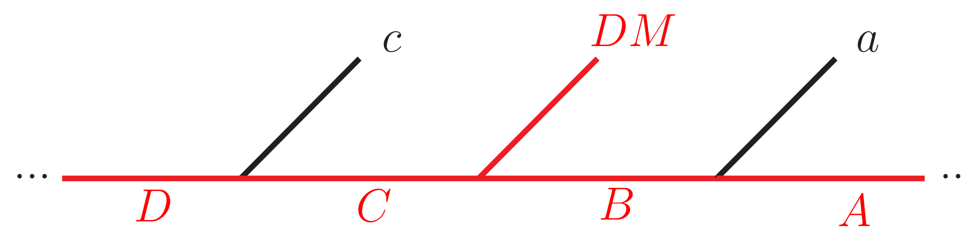

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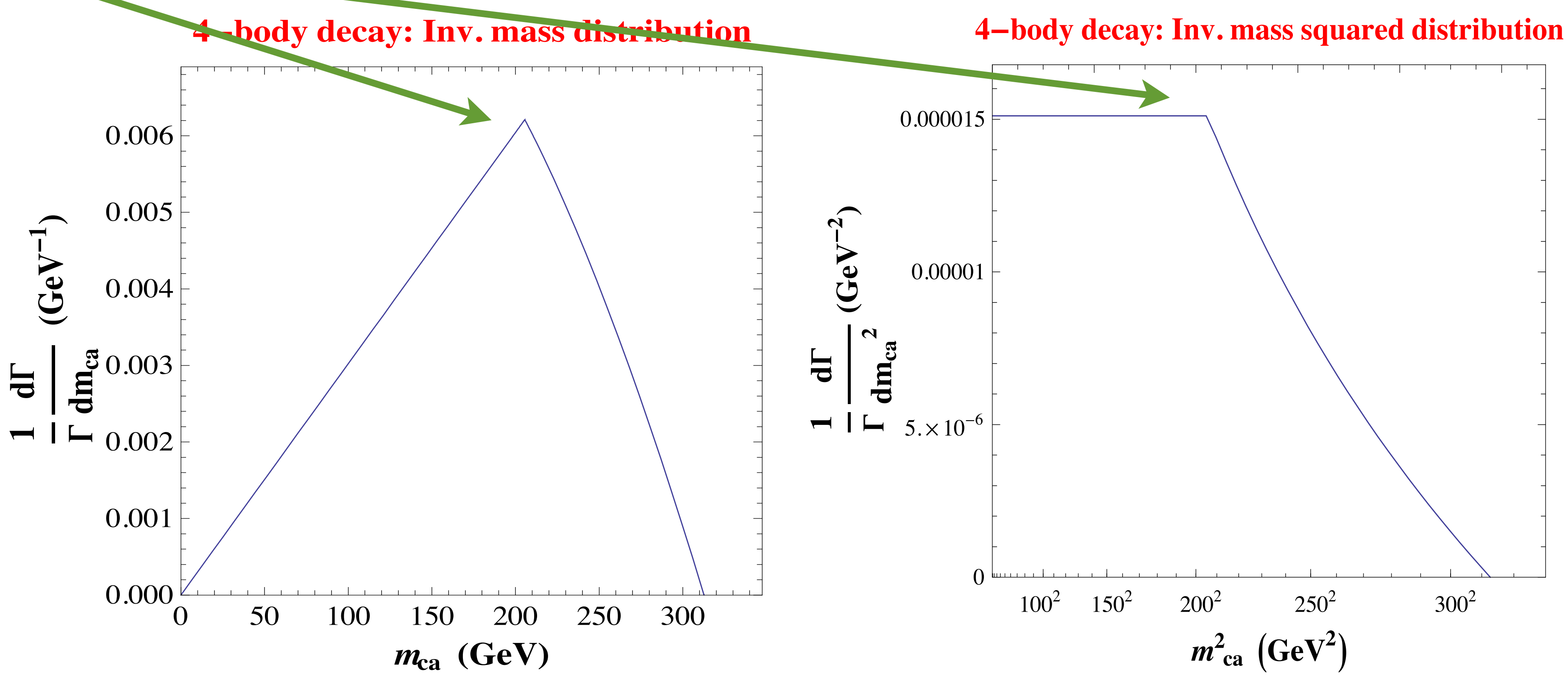
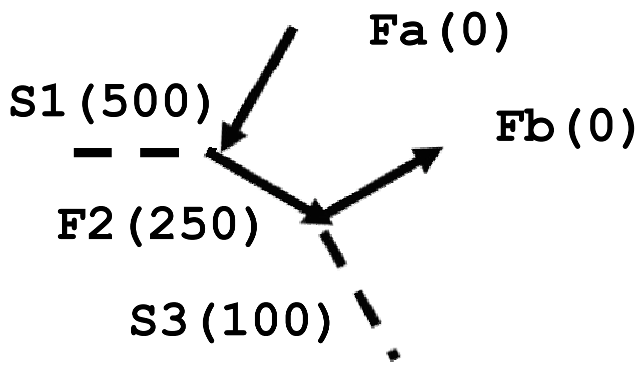


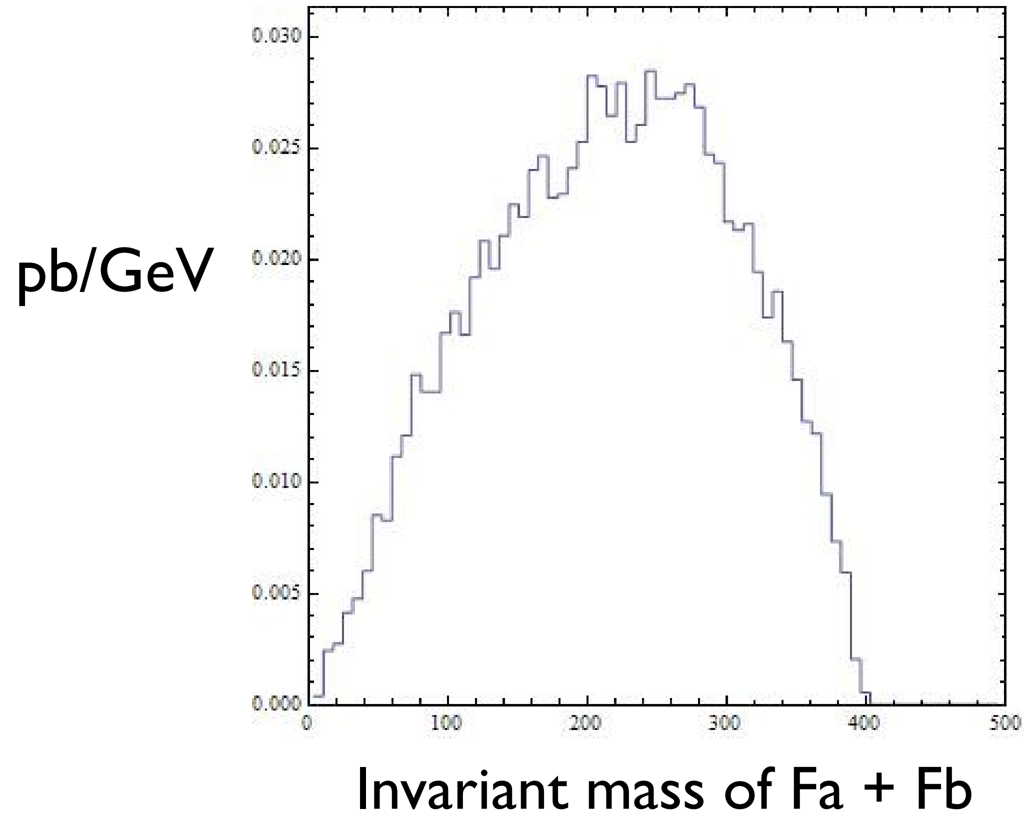
A, B, C and D have masses of 200, 400, 700 and 800 GeV

- Spin correlations important for signal!

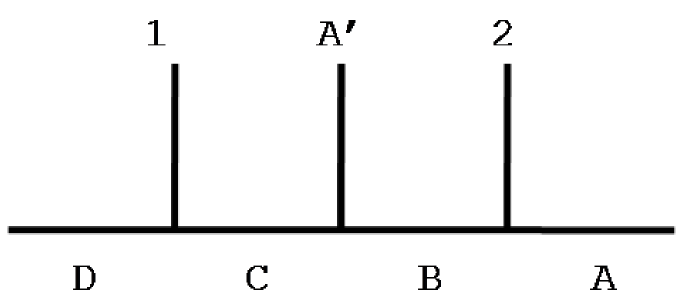
The Importance of Spin

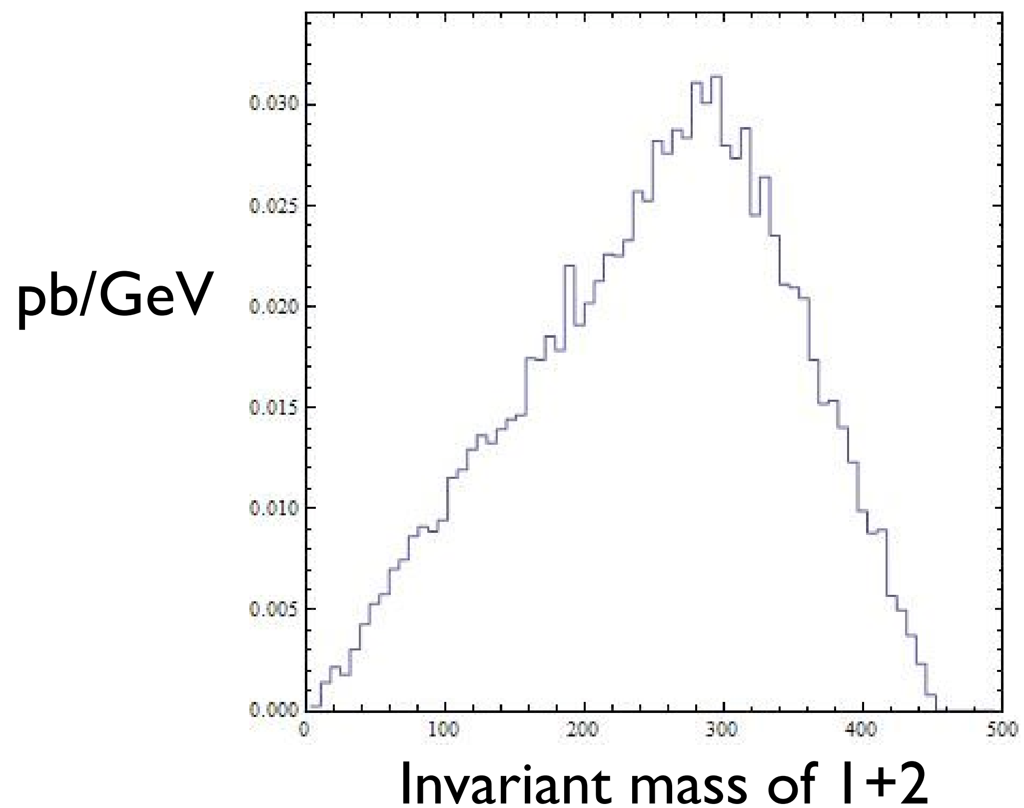


Left Chiral
- Right Chiral



Our signal process





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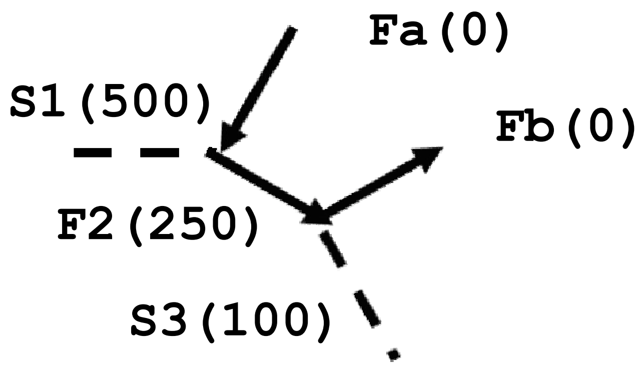

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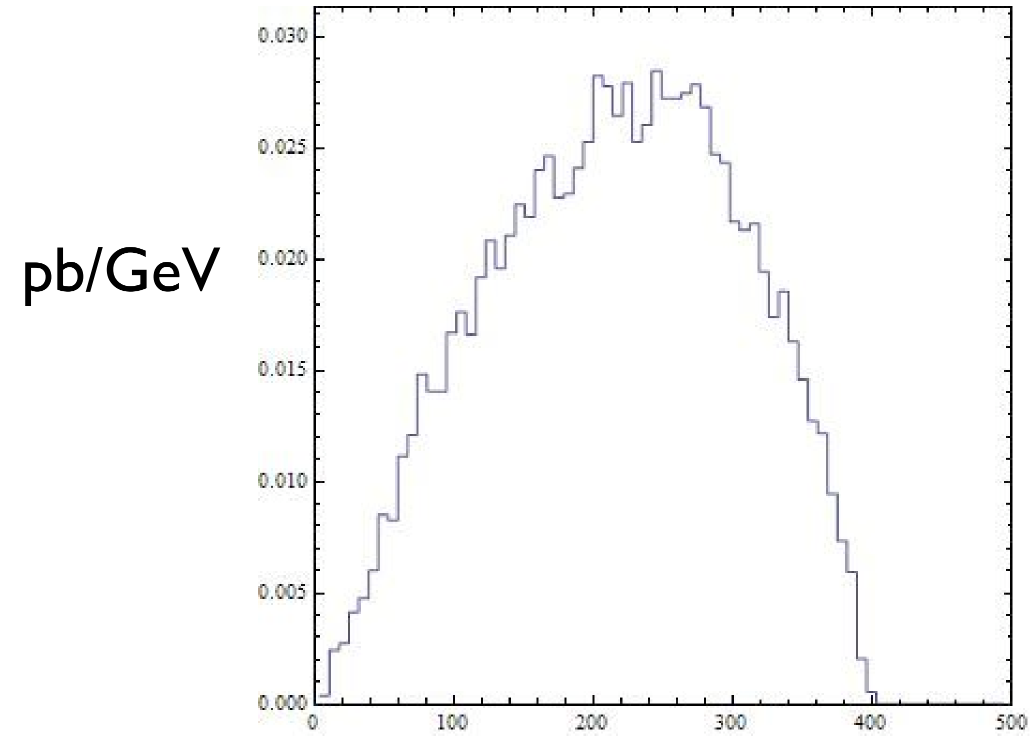
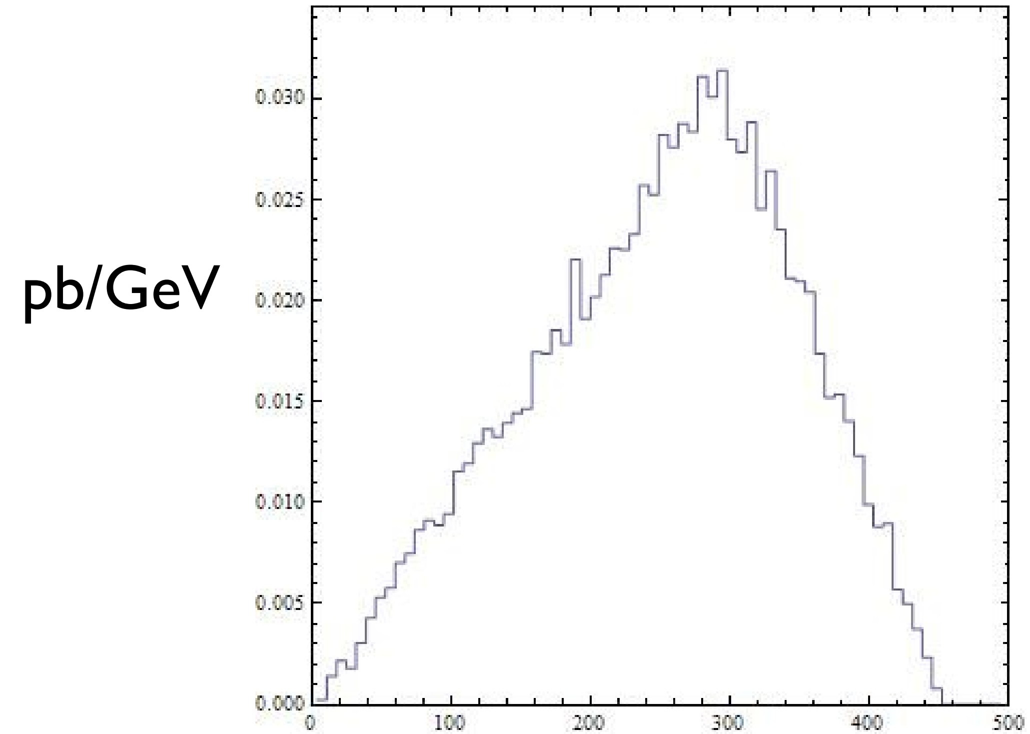


Invariant mass of Fa + Fb

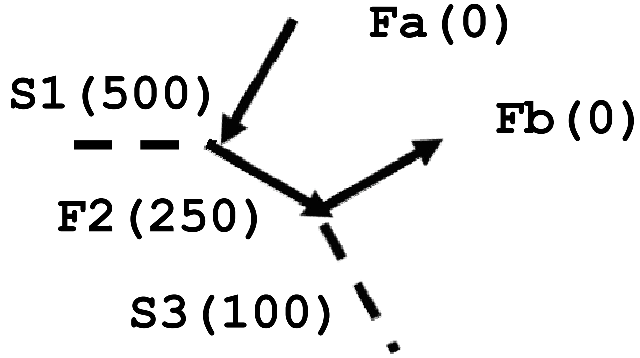
Analytically there is a derivative discontinuity in the cross section...

(no spin correlations)



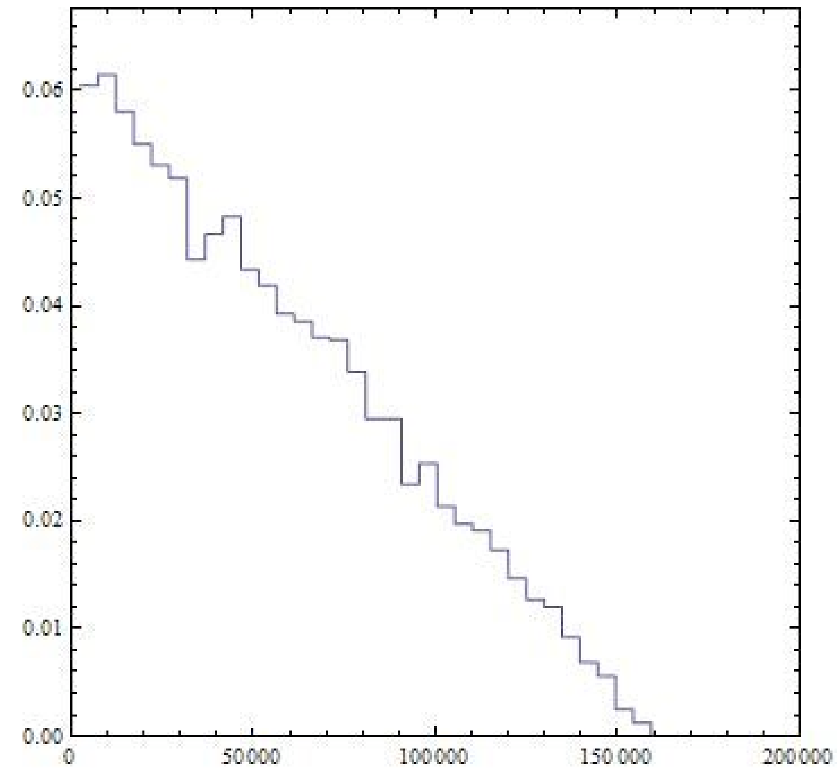
Invariant mass of 1+2

New Reconstruction



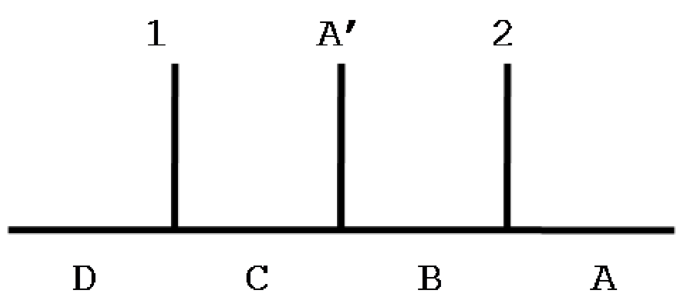
Left Chiral
- Right Chiral

pb/GeV

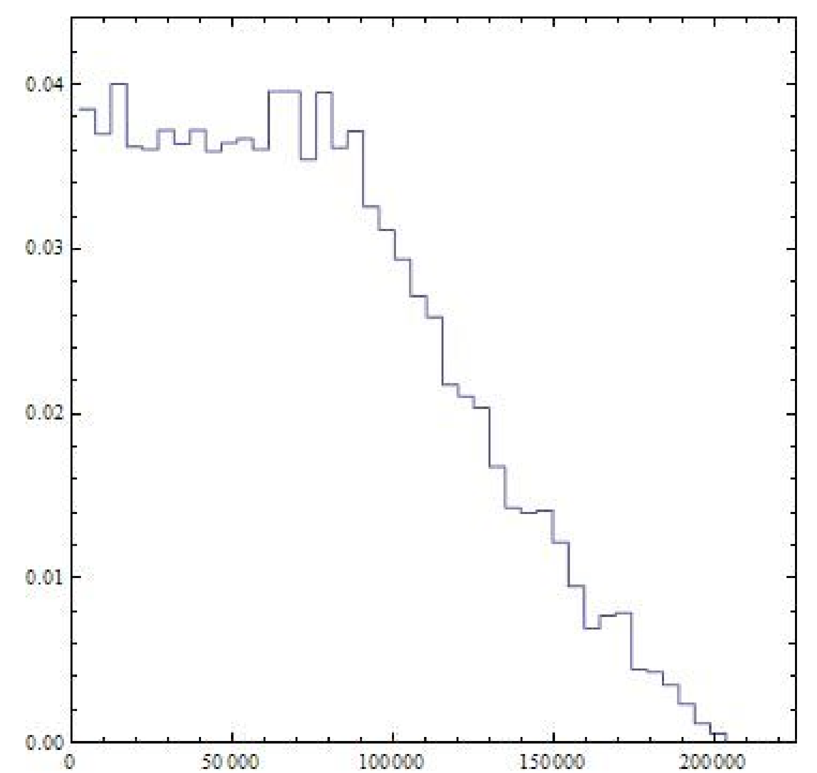


Invariant mass <u>squared</u> of Fa + Fb

Our signal process

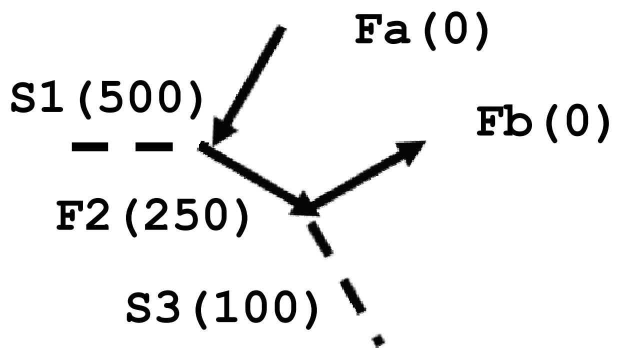


pb/GeV



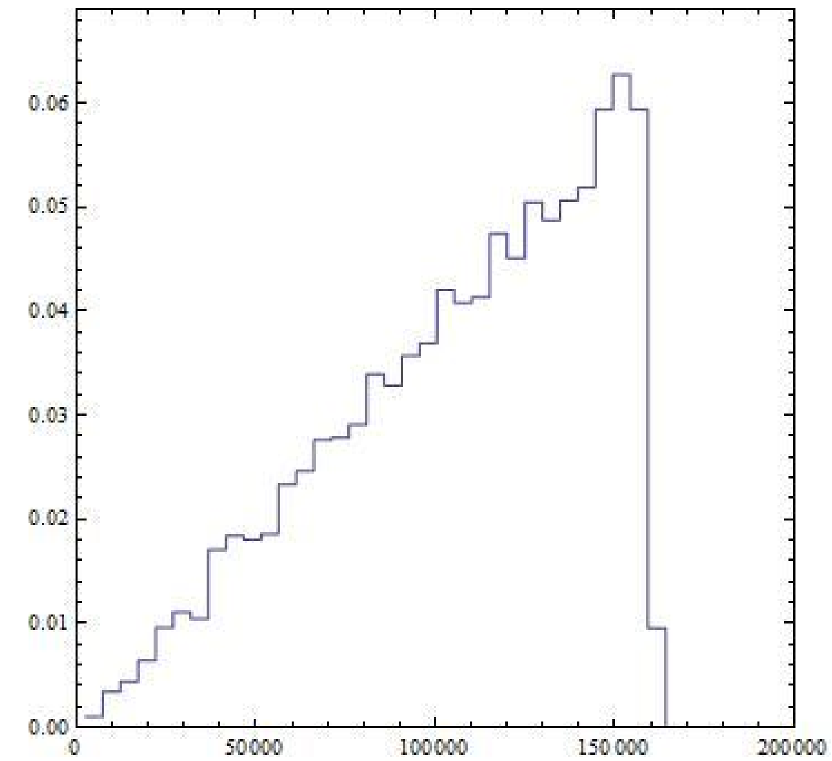
Invariant mass <u>squared</u> of 1+2

New Reconstruction



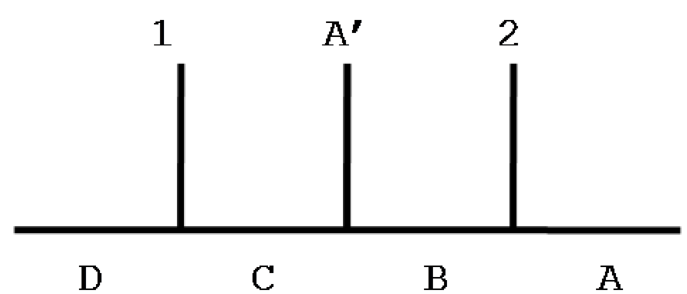
Left Chiral
- Left Chiral

pb/GeV

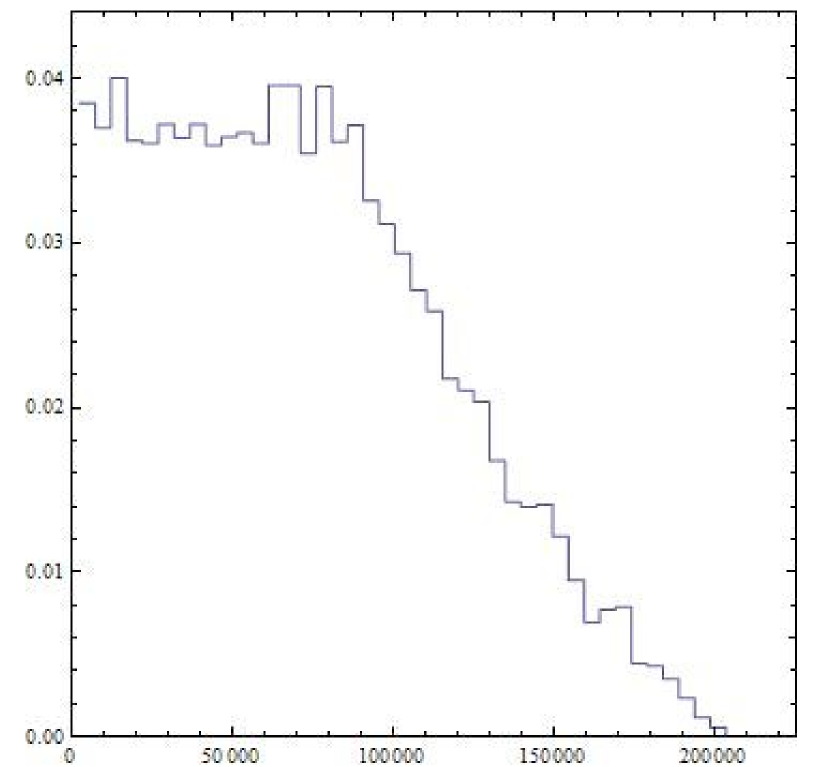


Invariant mass <u>squared</u> of Fa+Fb

Our signal process

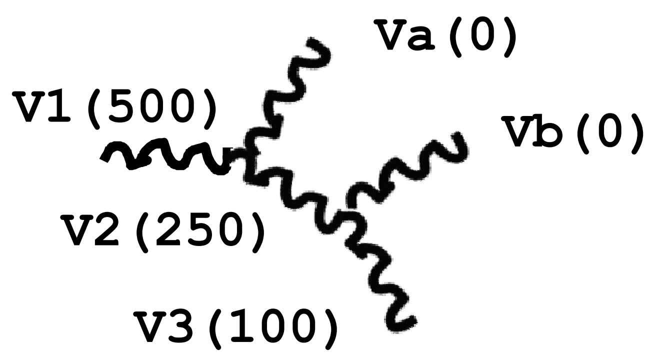


pb/GeV

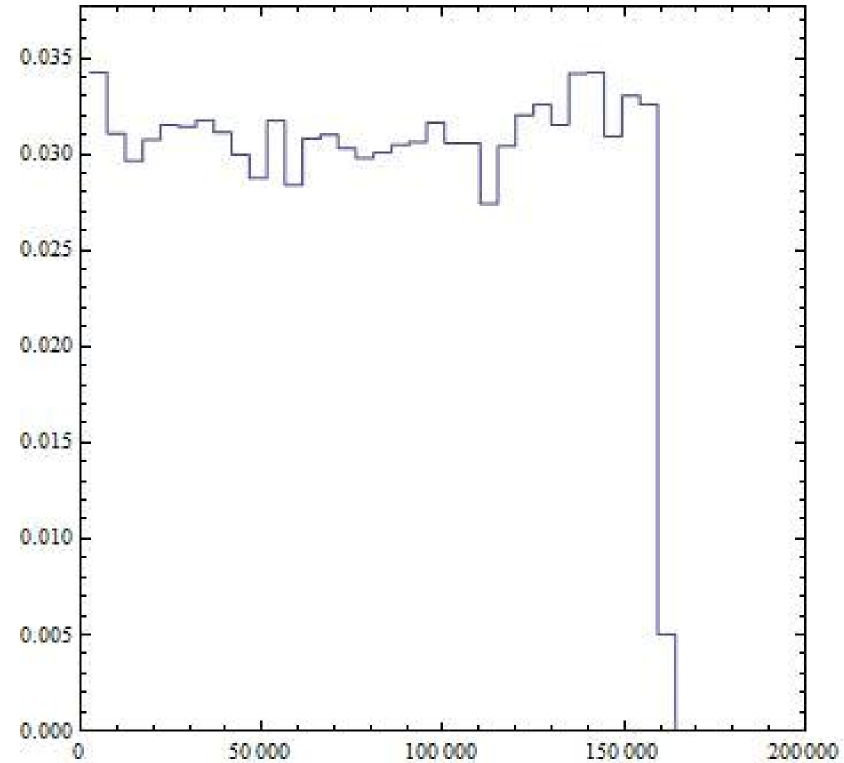


Invariant mass <u>squared</u> of 1+2

New Reconstruction

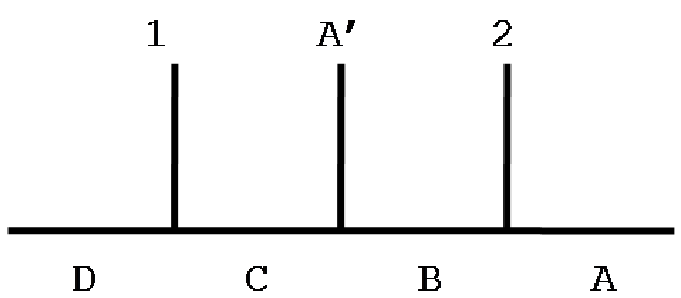


pb/GeV

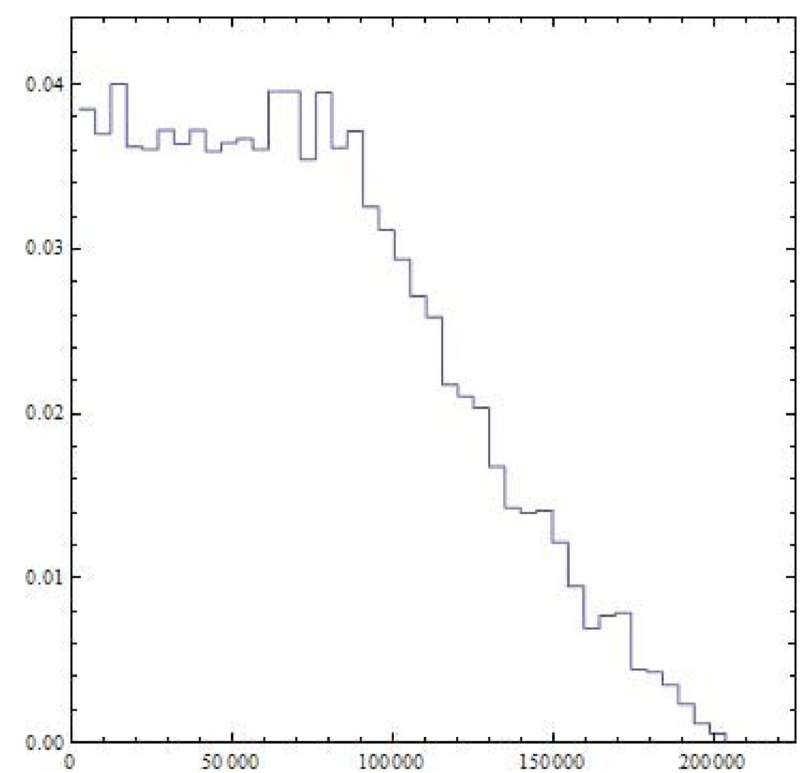


Invariant mass <u>squared</u> of Va+Vb

Our signal process



pb/GeV

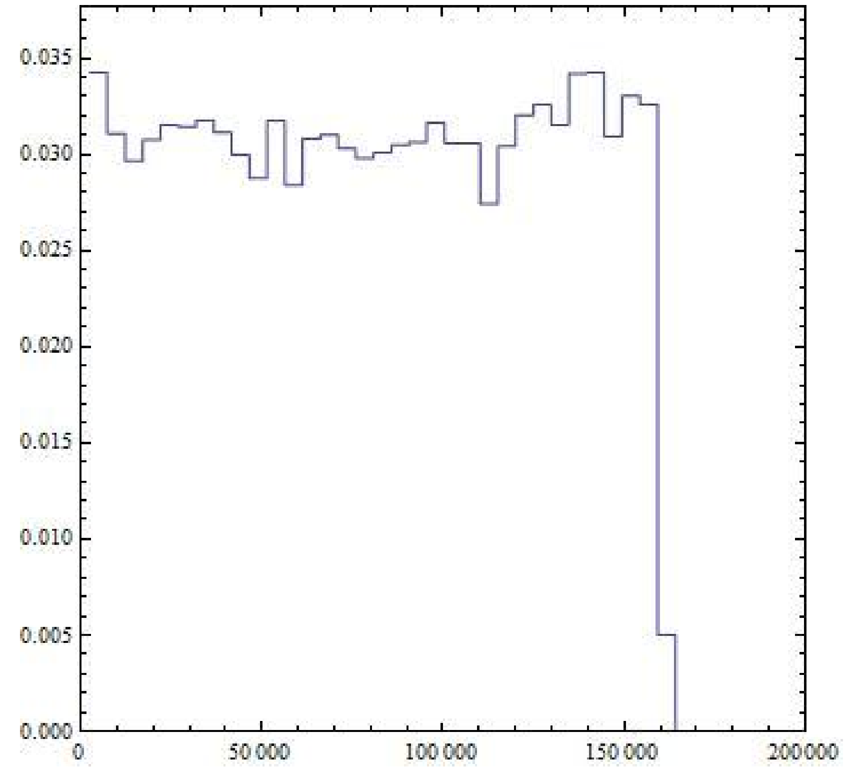


Invariant mass <u>squared</u> of 1+2

New Reconstruction

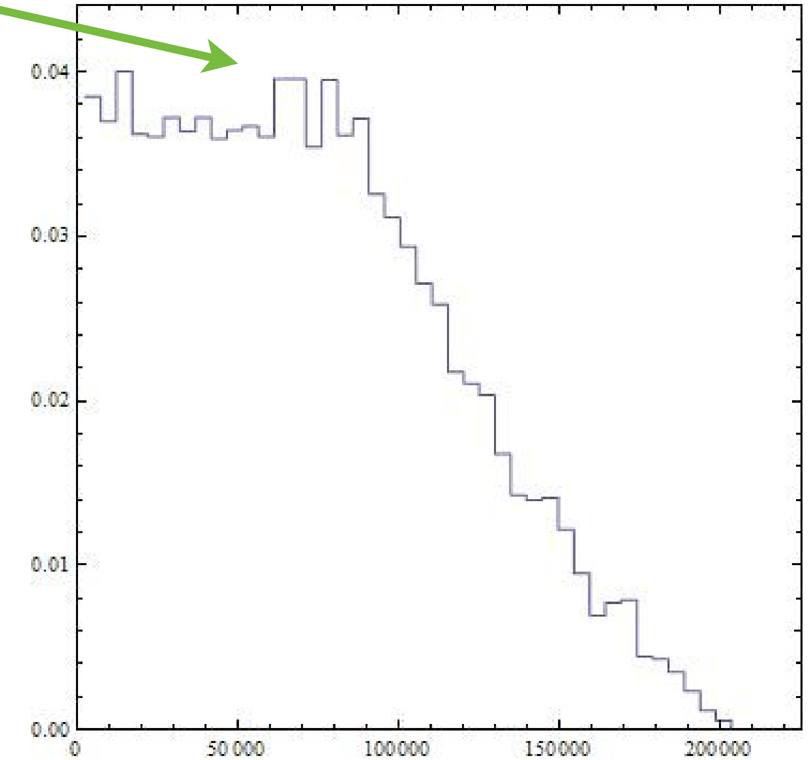
No matter the process
this structure is unique

pb/GeV



Invariant mass squared of Va+Vb

pb/GeV

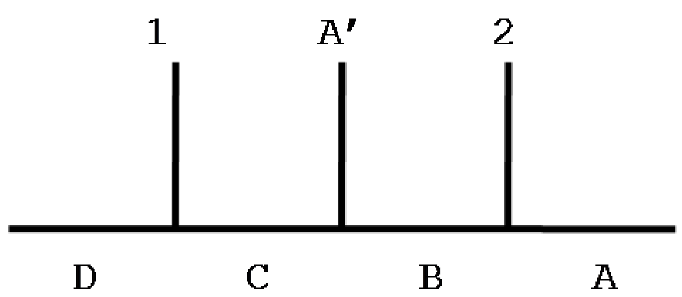


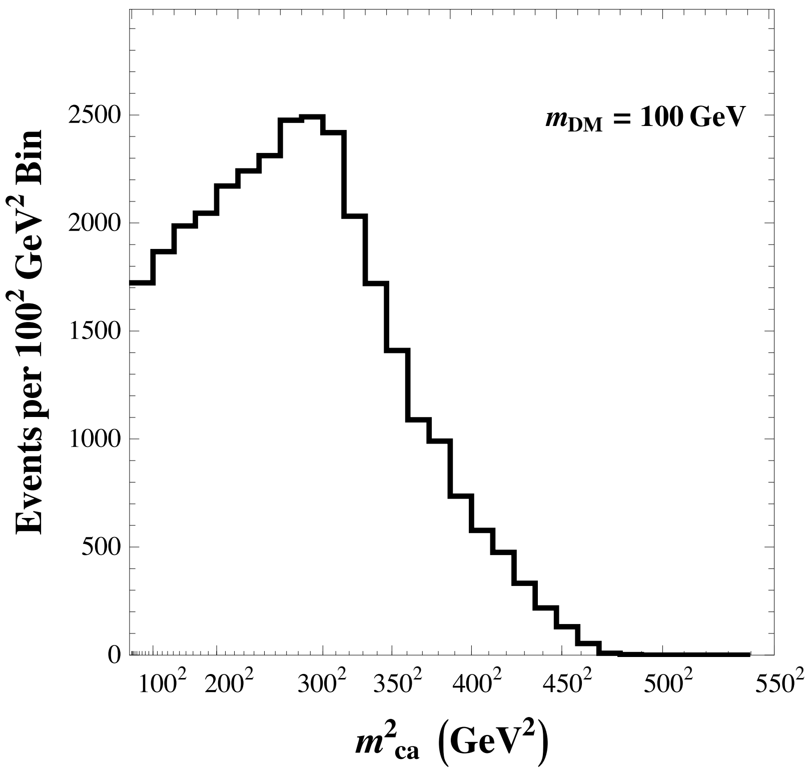
Invariant mass squared of 1+2

New Reconstruction

Our signal process

(with spin correlations)





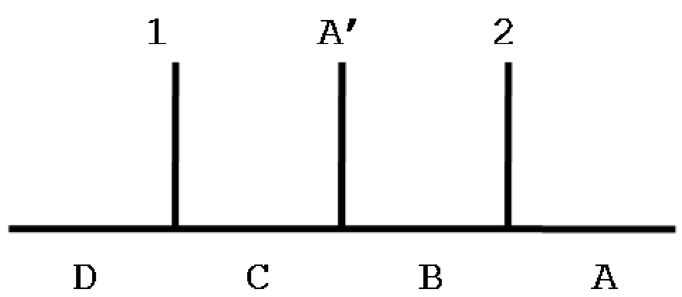
Invariant mass squared of 1+2

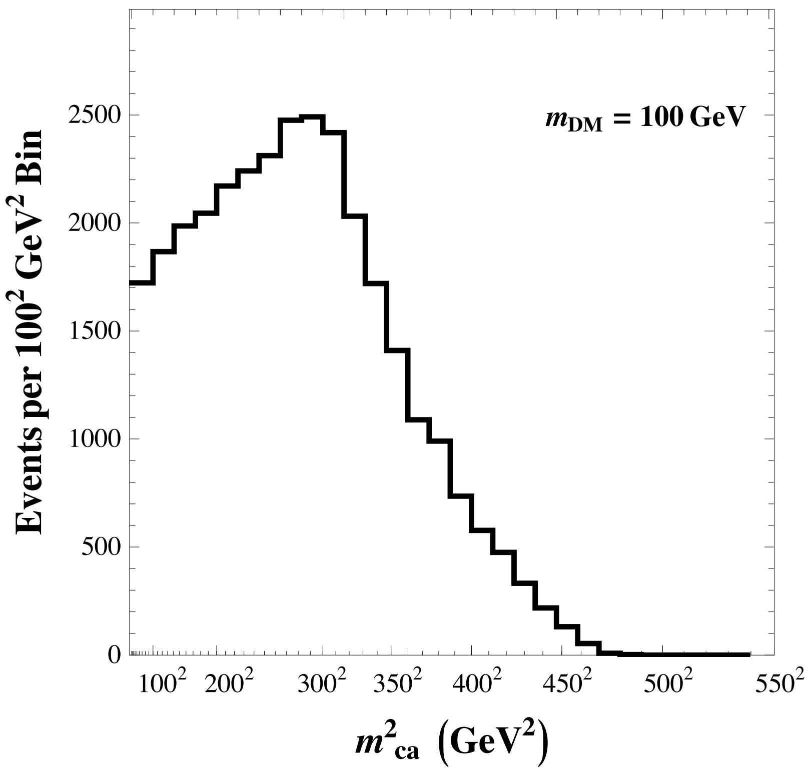
- Exotic example: B and C is spin 1 and 1/2. Chiral couplings.

New Reconstruction

Our signal process

(with spin correlations)



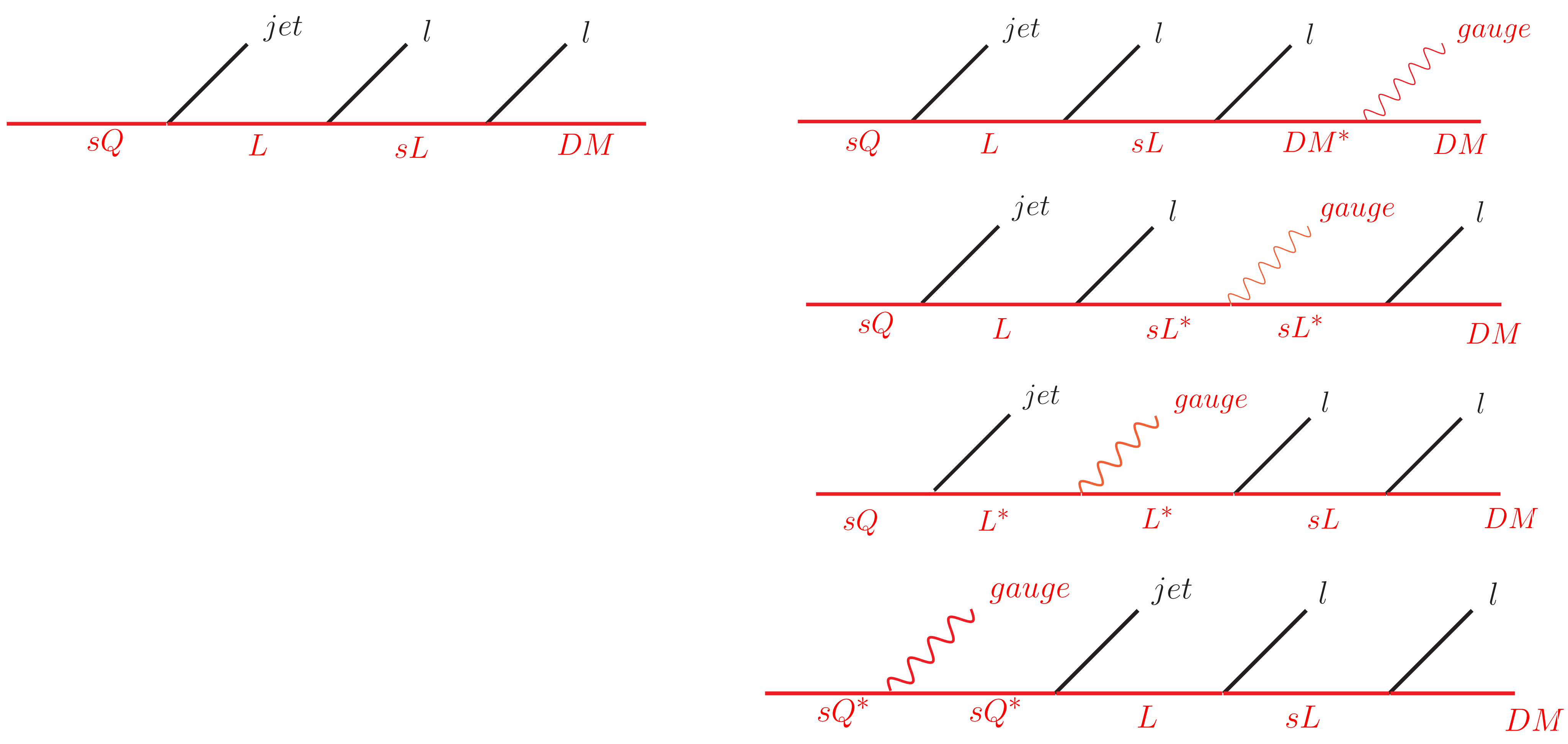


Invariant mass squared of 1+2

- Exotic example: B and C is spin 1 and 1/2. Chiral couplings.
- How does this feature hold up to acceptance and detector cuts?

New Reconstruction w/ Cuts

- Consider the following processes:



$m_Q = 700$ GeV $\quad m_L = 650$ GeV $\quad m_{sL} = 300$ GeV $\quad m_\chi = 100$ GeV $\quad m_V = 100$ GeV

New Reconstruction w/ Cuts

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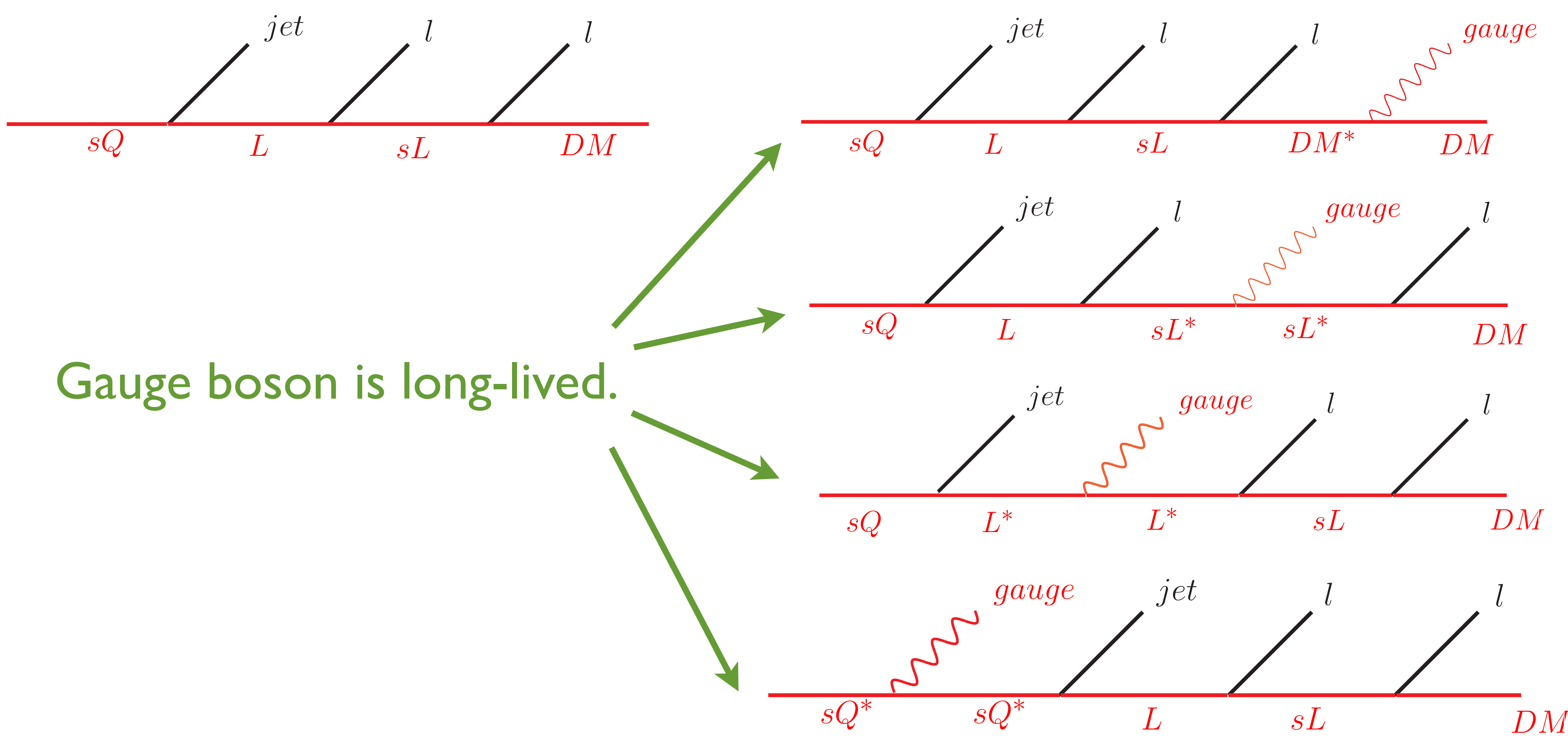

$$m_Q = 700 \text{ GeV} \quad m_L = 650 \text{ GeV} \quad m_{sL} = 300 \text{ GeV} \quad m_\chi = 100 \text{ GeV} \quad m_V = 100 \text{ GeV}$$

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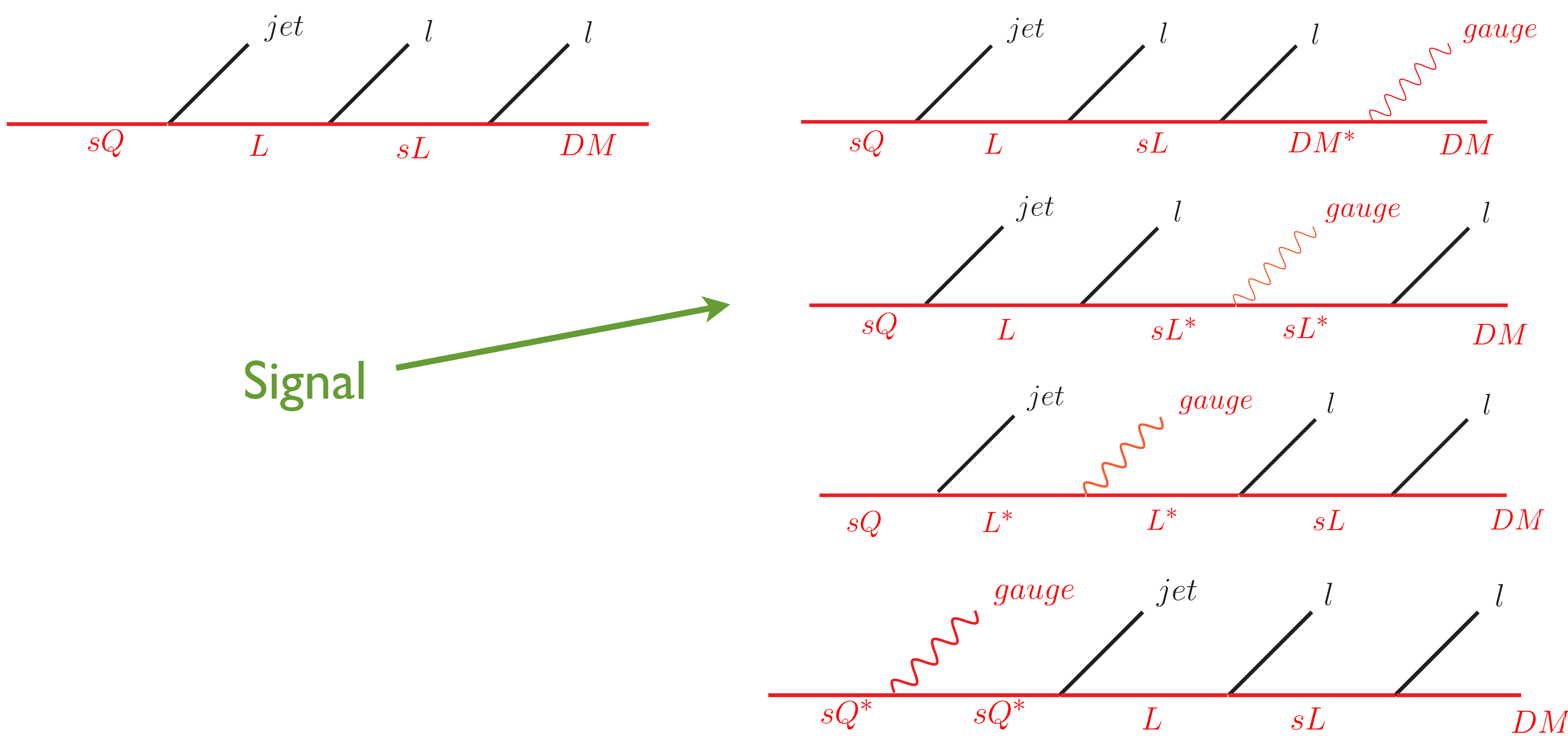

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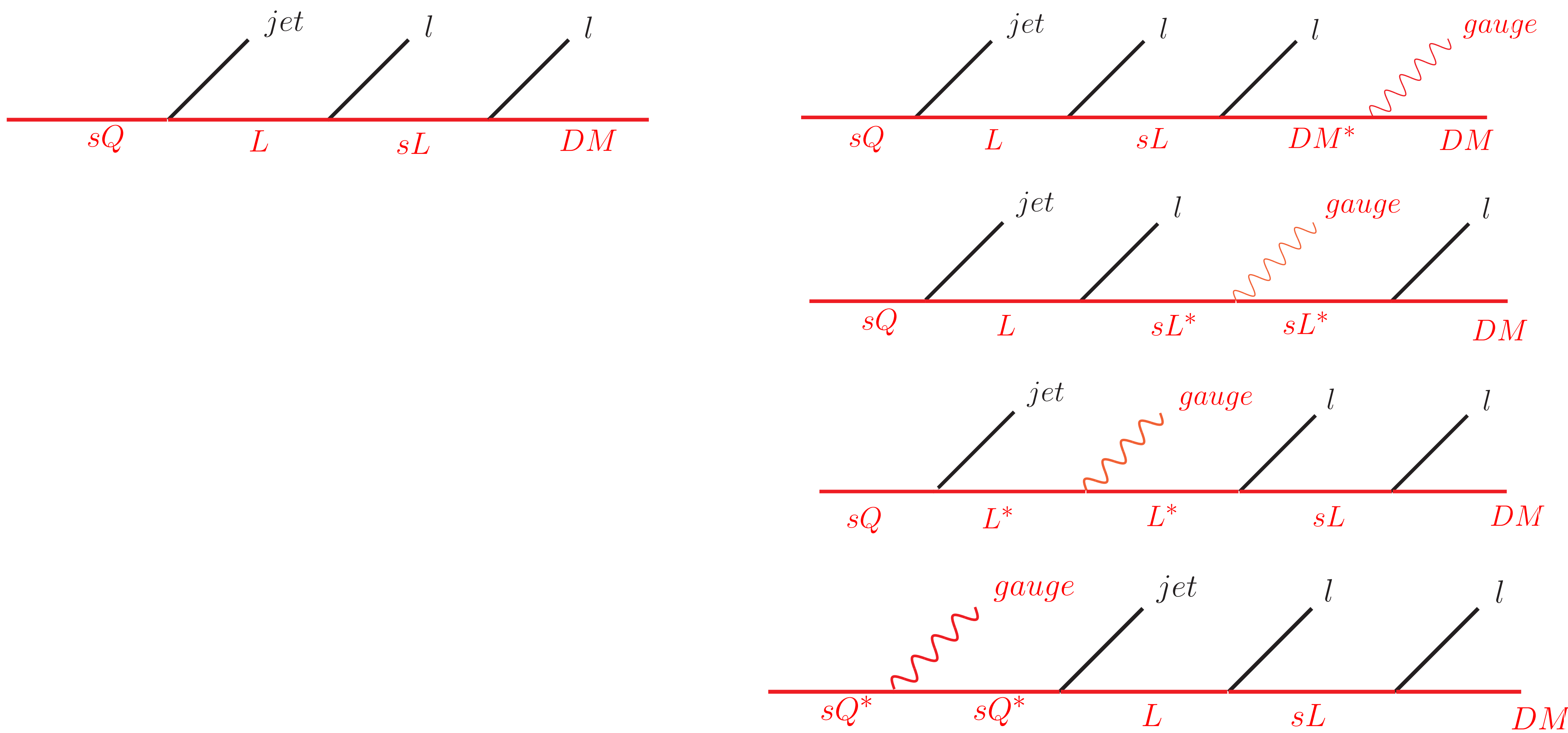

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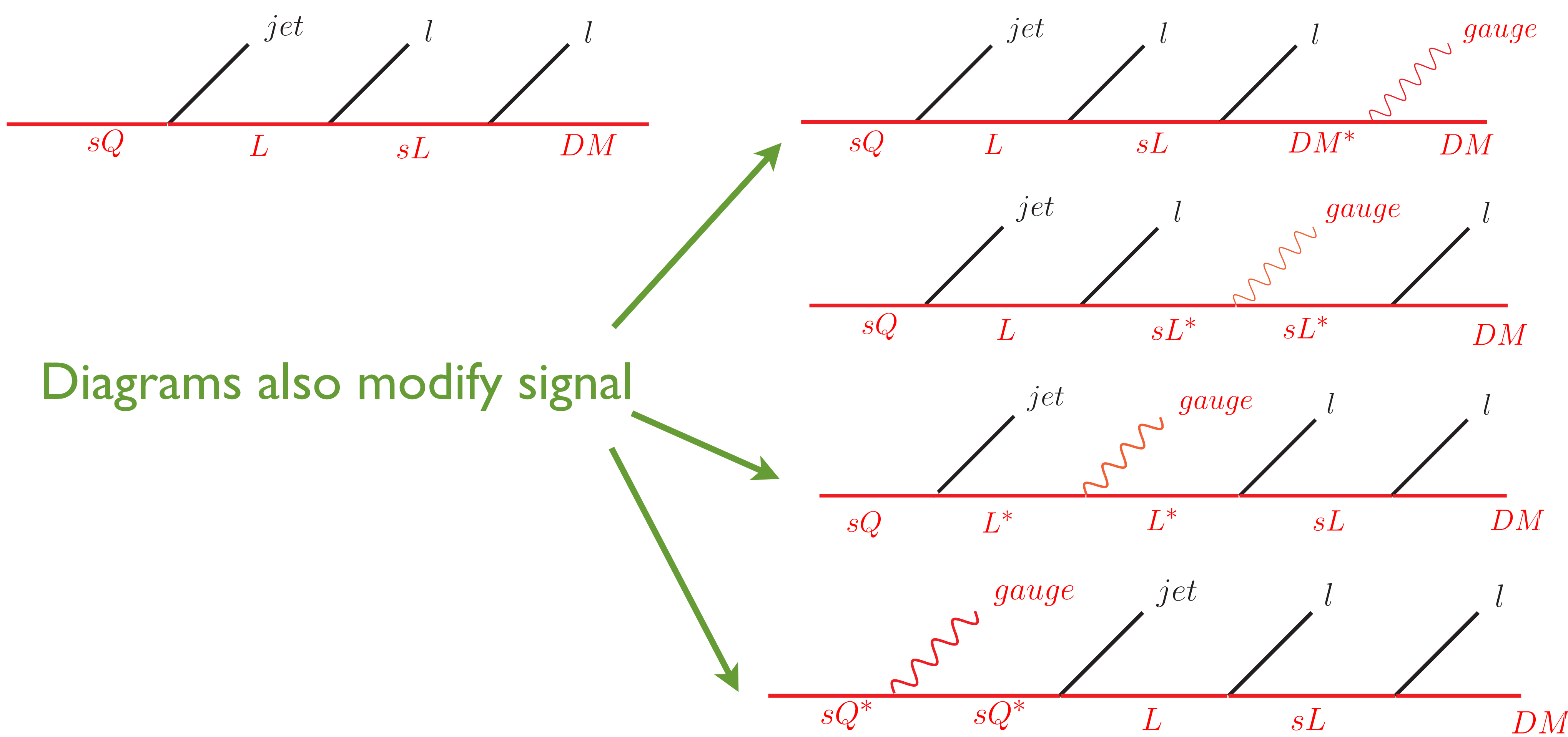


$m_Q = 700$ GeV $\quad m_L = 650$ GeV $\quad m_{sL} = 300$ GeV $\quad m_\chi = 100$ GeV $\quad m_V = 100$ GeV

New Reconstruction w/ Cuts

- Acceptance and background cuts consistent with ATLAS and CMS:

$$|\eta_l| < 2.5, \qquad |\eta_j| < 2.5,$$
$$\Delta R_{ll} > 0.3, \qquad \Delta R_{lj},\, \Delta R_{jj} > 0.4.$$

1. Two leptons with $p_T > 20$ GeV
2. At least one leading jet with $p_T > 100$ GeV and subleading jets with $p_T > 50$ GeV
3. $\not{E}_T > 100$ GeV and $\not{E}_T > 0.2\, M_{\text{eff}}$
4. Transverse sphericity $S_T > 0.2$.

- Detector effects: Simple gaussian smearing

$$\frac{\Delta E_e}{E_e} = \frac{10\%}{\sqrt{E_e(\text{GeV})}} \oplus 0.7\%, \qquad \frac{\Delta E_j}{E_j} = \frac{50\%}{\sqrt{E_j(\text{GeV})}} \oplus 3\%.$$

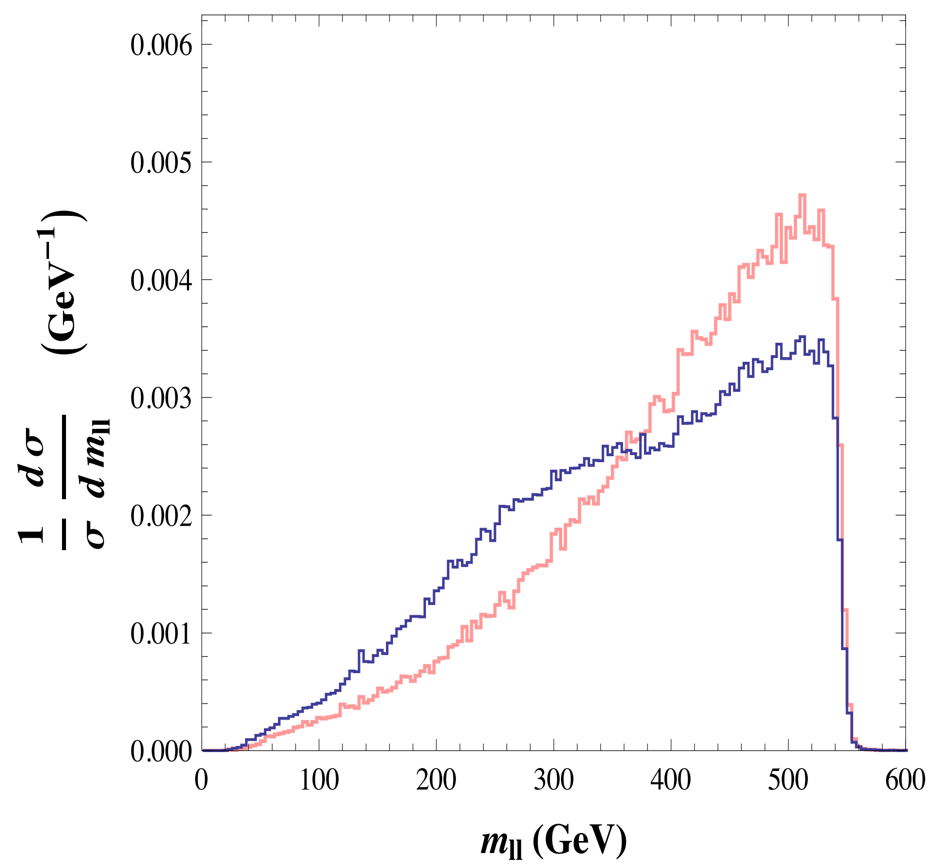
Backgrounds
(in one transparency)

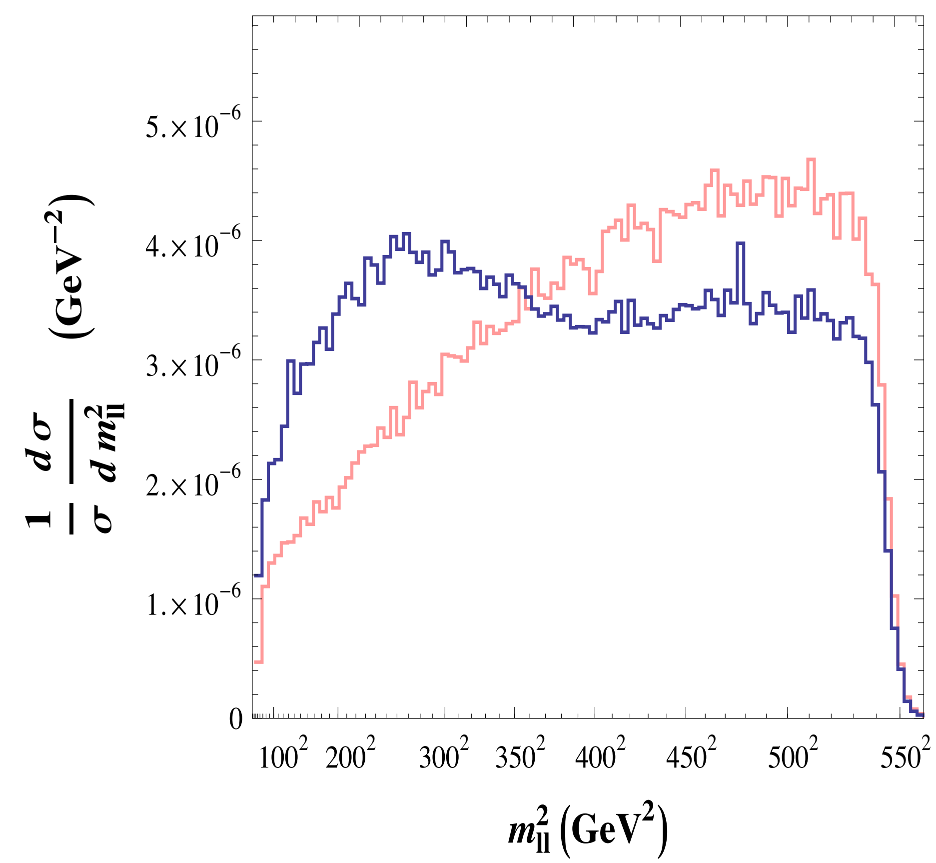
Background	Events (1 fb^{-1})
$t\bar{t}$	81.5
$W+$ jets	1.97
$Z+$ jets	1.20
QCD	0
Total SM	84.67

- Additional signal background: Invisible Z decays

New Reconstruction w/ Cuts

- Dilepton invariant mass
  (with additional diagrams and cuts)





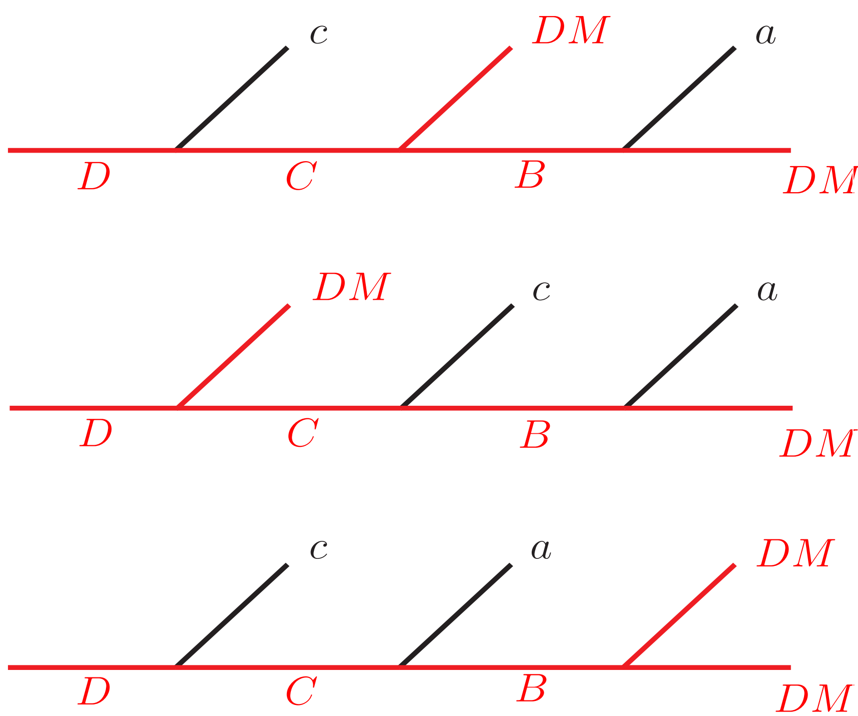
$S/B = 0.08$

$S/\sqrt{B} = 18.6$

Part II: Topologies and MT2 Reconstruction

Many New Topologies

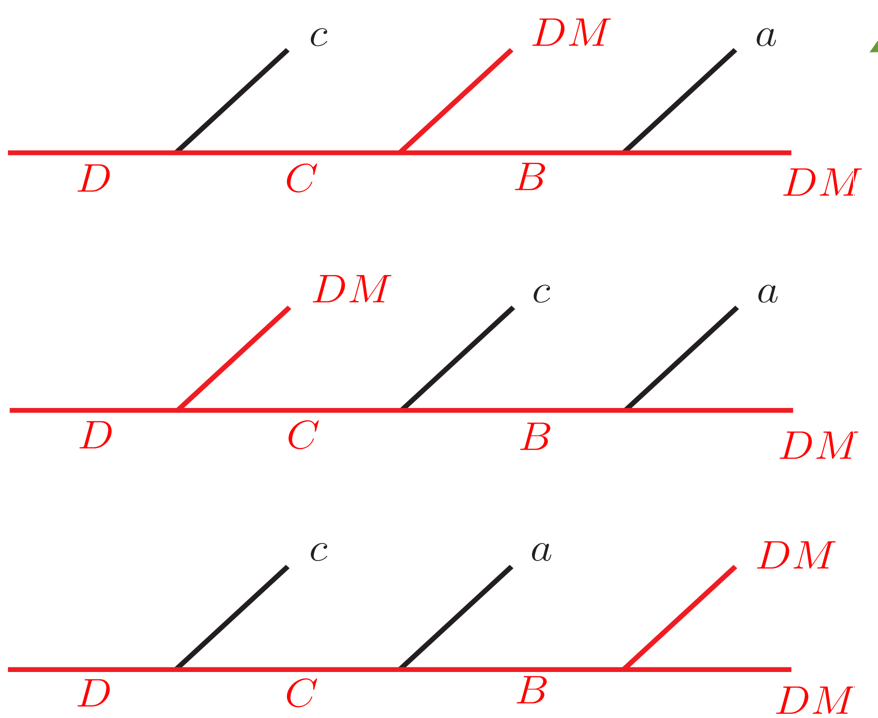
- So far focused on one topology



Many New Topologies

- So far focused on one topology

Discussed this topology first.



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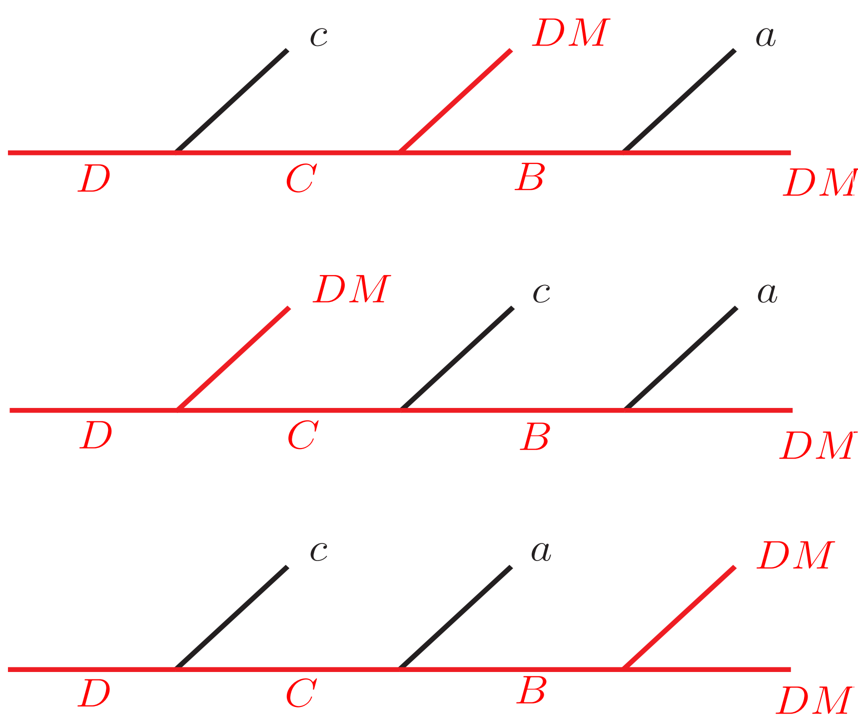

Discussed this topology first.

If these topologies exist, we want to account for them.

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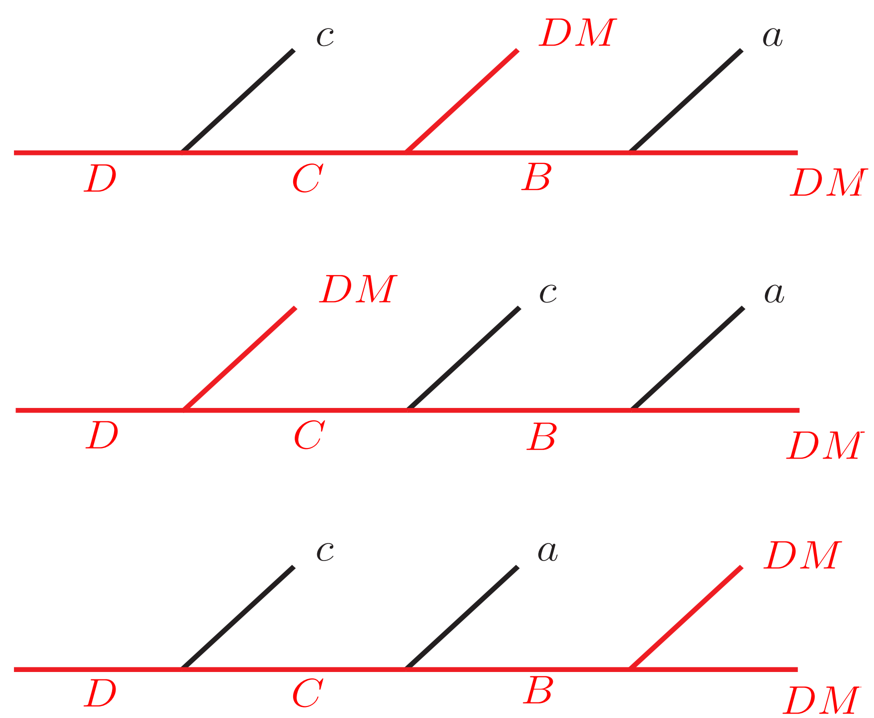

If these topologies exist, we want to account for them.

- Emphasize: Models with “non-parity” stabilization symmetries can have more than one DM per leg. Use MT2 to tell the difference.

What is MT2?

- Basically the transverse mass:

$$\left(M_T^{(i)}\right)^2 = \left(m_T^{v(i)}\right)^2 + \tilde{m}^2 + 2\left(E_T^{v(i)}\tilde{E}_T^{(i)} - \mathbf{p}_T^{v(i)} \cdot \tilde{\mathbf{p}}_T^{(i)}\right)$$

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Visible transverse mass

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Missing mass (or trial mass)

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Missing Transverse Momentum

Visible transverse mass

Transverse mass

- Minimize transverse mass for each decay leg

$$M_{T2} \equiv \min_{\mathbf{p}_T^{v(1)} + \mathbf{p}_T^{v(2)} + \not{\mathbf{p}}_T = 0} \left[\max\left\{M_T^{(1)},\ M_T^{(2)}\right\}\right]$$

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Transverse energy

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Missing Transverse Energy

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Maximum value over many events

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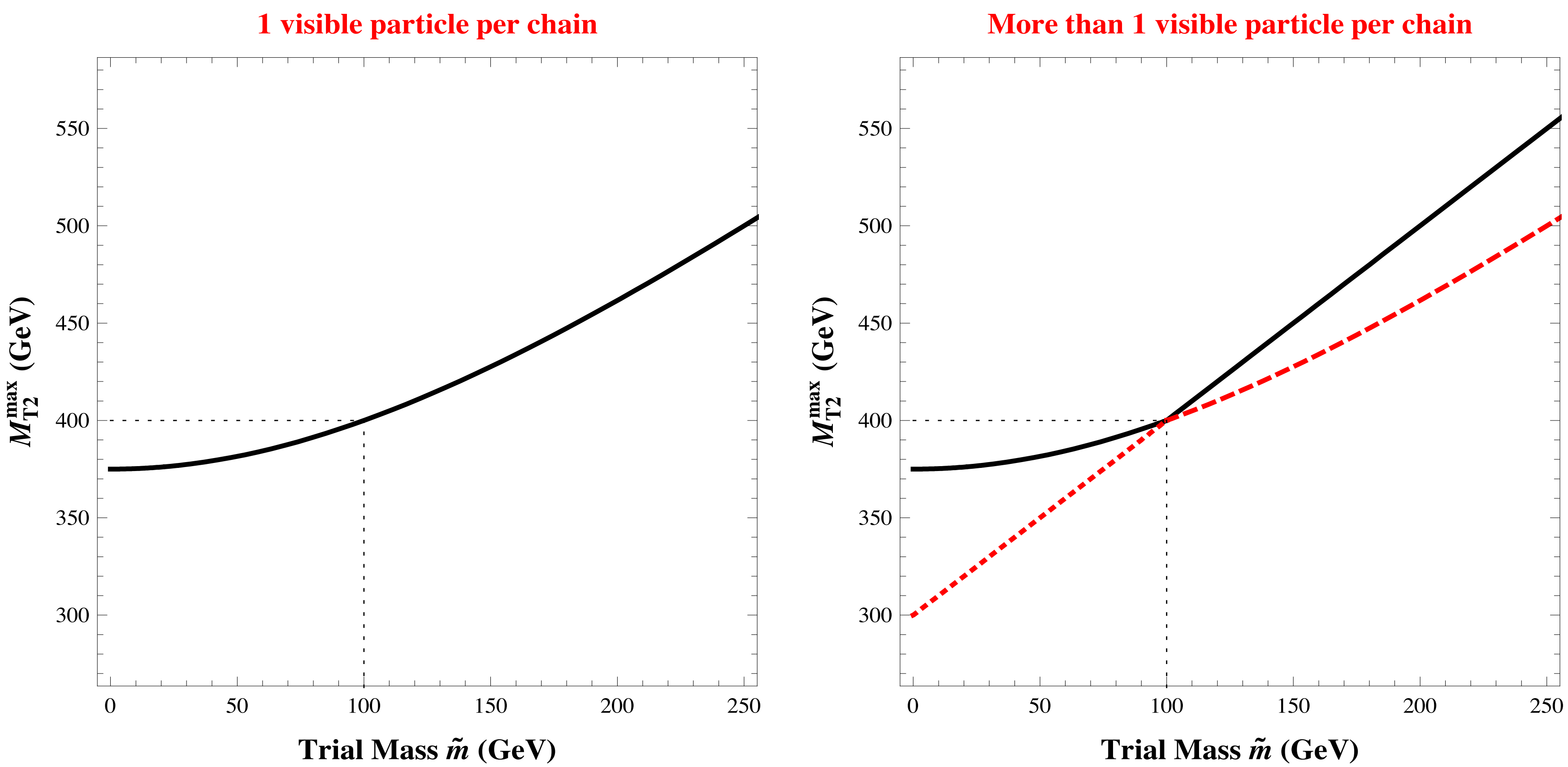
Maximum value over many events

$$M_{T2}^{\max}(\tilde{m}) = \max_{\text{many events}}\left[M_{T2}(\tilde{m})\right]$$

Dependent on trial mass

What is MT2?

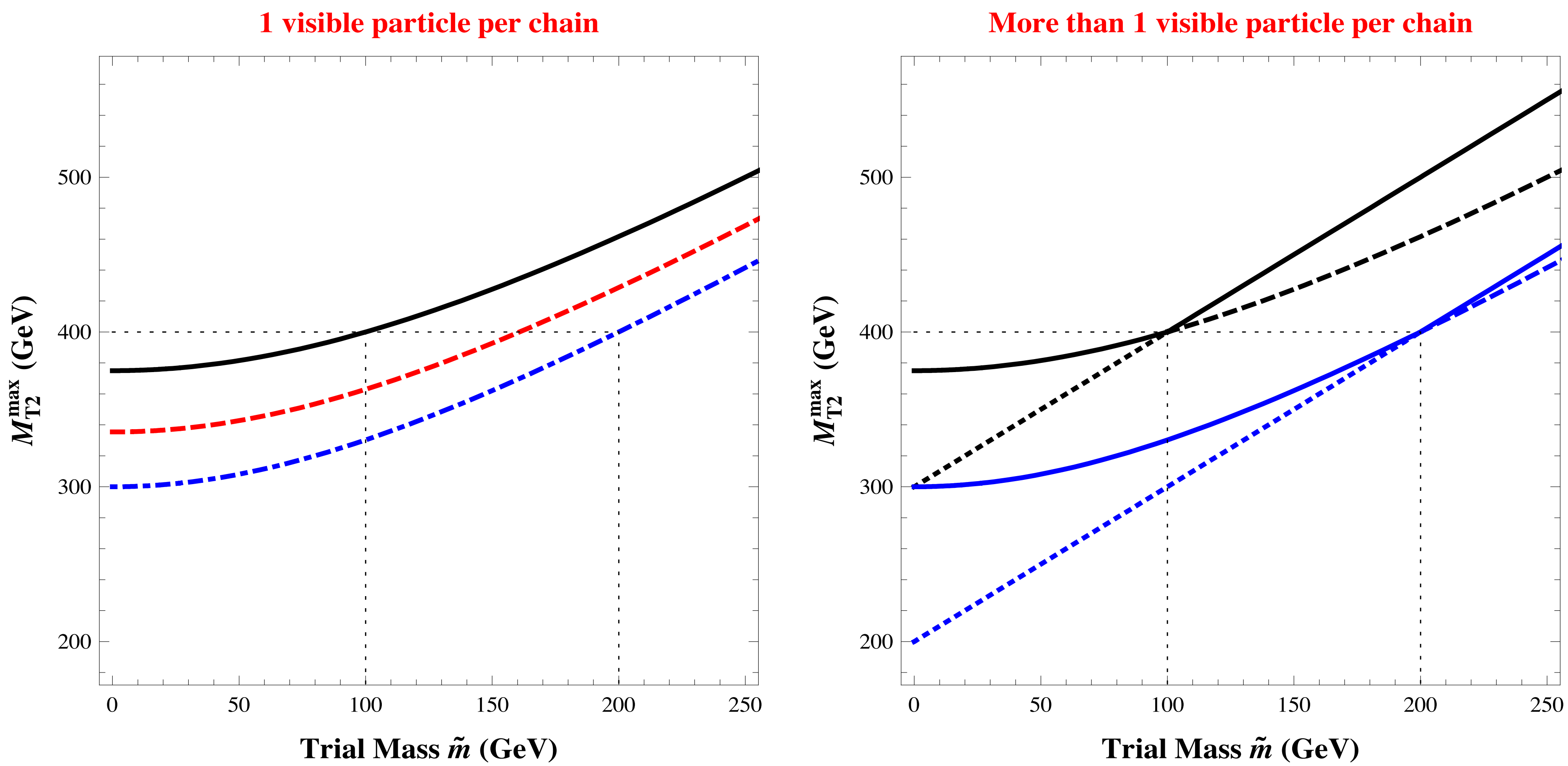
- Generates a "kink" structure for Z2 models:



(Mother/DM mass of 400/100 GeV)

What is MT2?

- Generates a "kink" structure for "non-parity" models!



(Mother/DM mass of 400/100 GeV)

(Trial mass of 25 GeV)

What is MT2?

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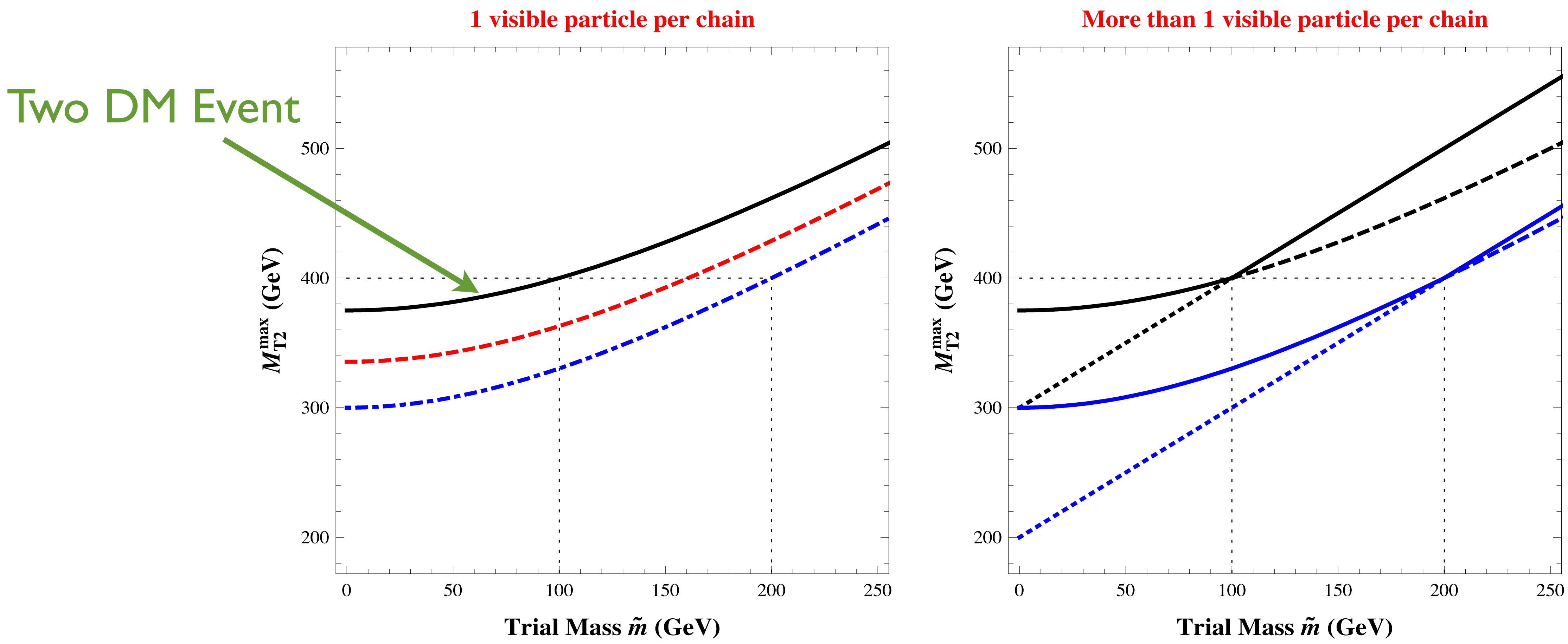

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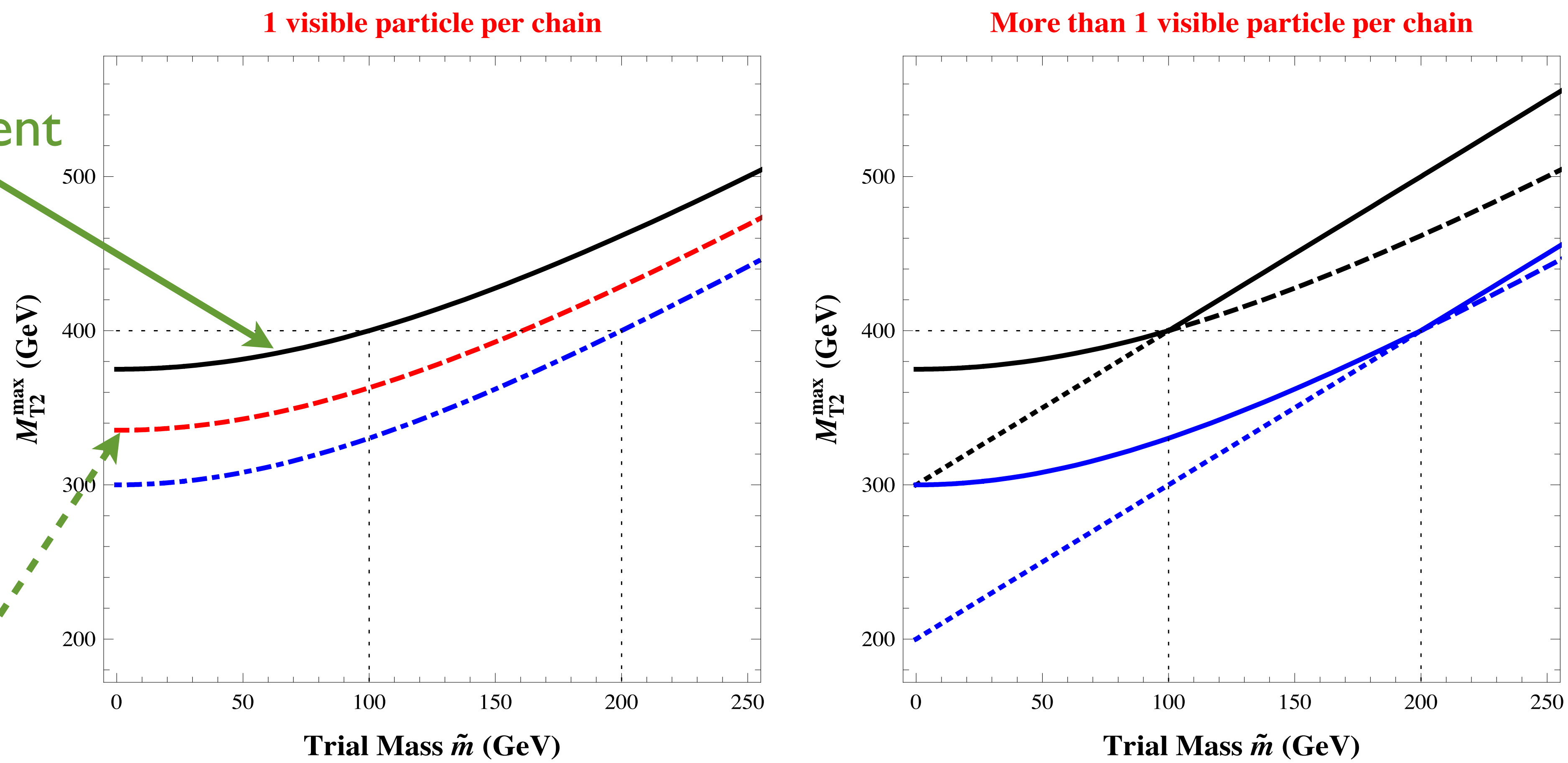
Two DM Event



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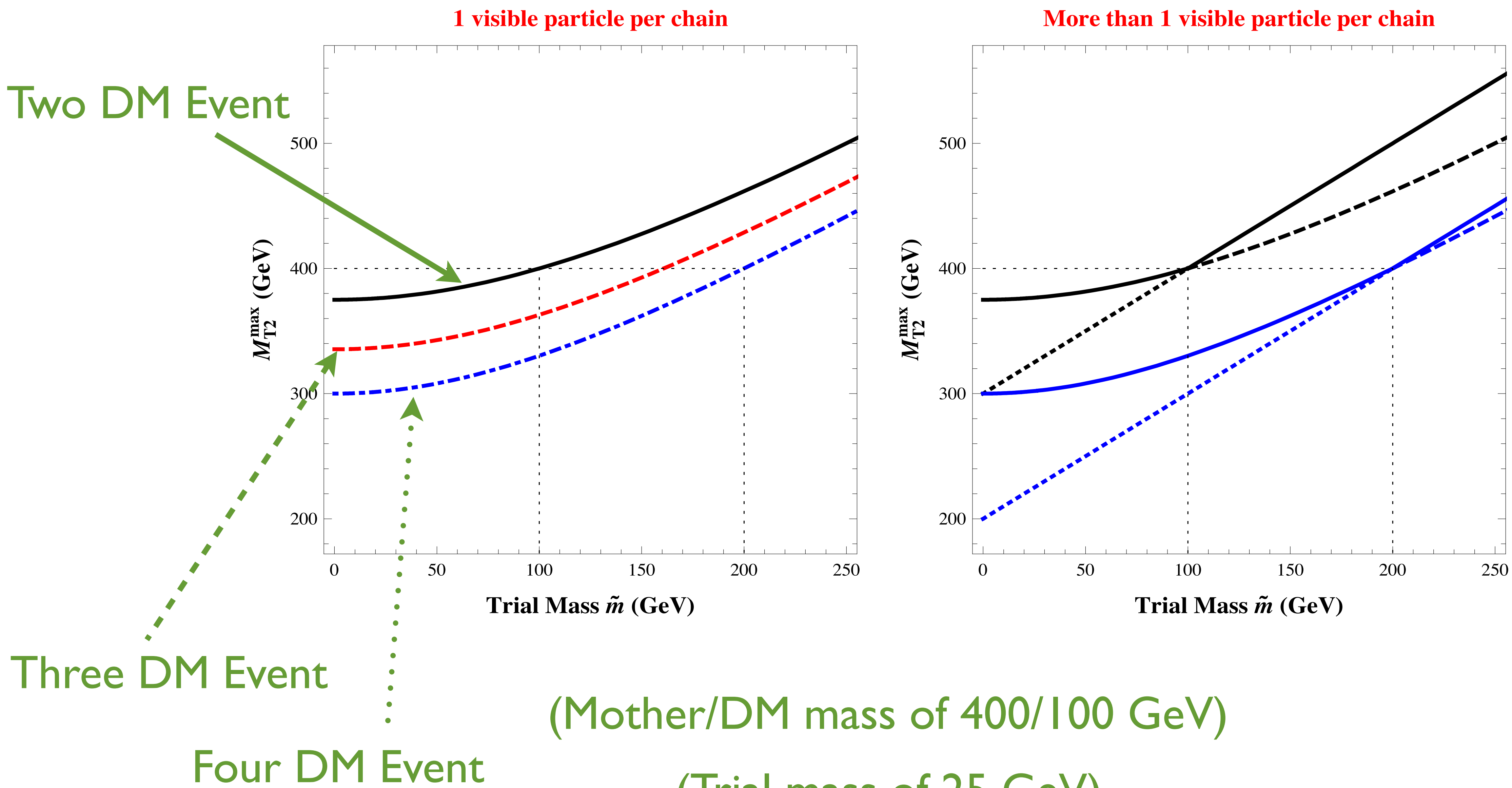

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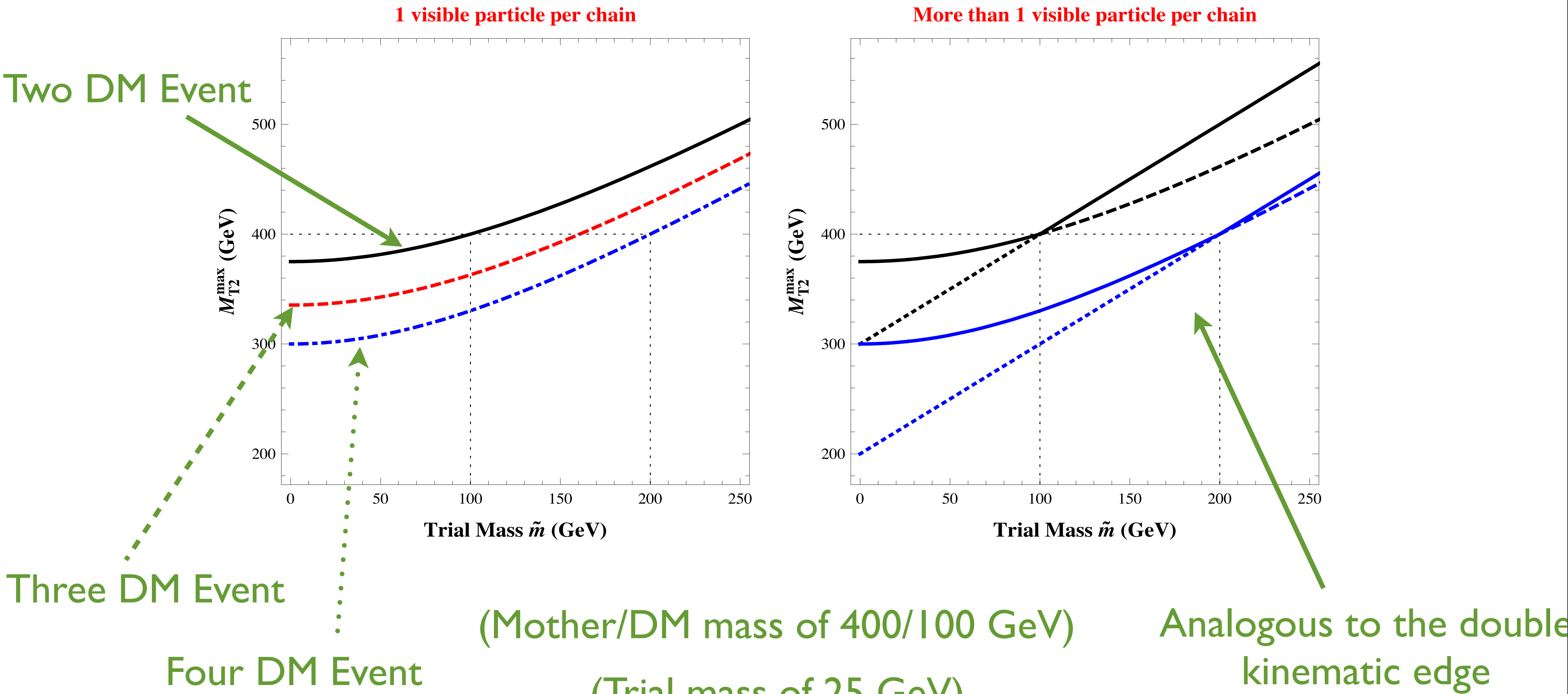


(Mother/DM mass of 400/100 GeV)

(Trial mass of 25 GeV)

What is MT2?

- Highly dependent on properly reconstructing events. (Address this in the future).

“Non-parity” and MT2

- Care required in seeing “non-parity signal” over Z2 bkg.

“Non-parity” and MT2

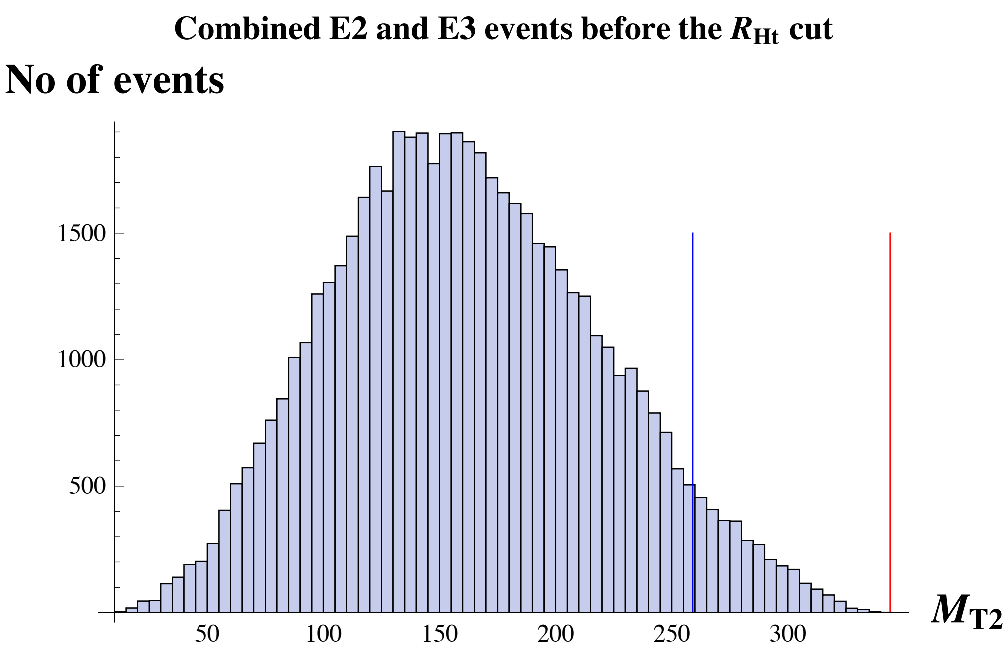
- Care required in seeing “non-parity signal” over Z2 bkg.
  - Define a ratio of the sum of the visible pT on each leg.

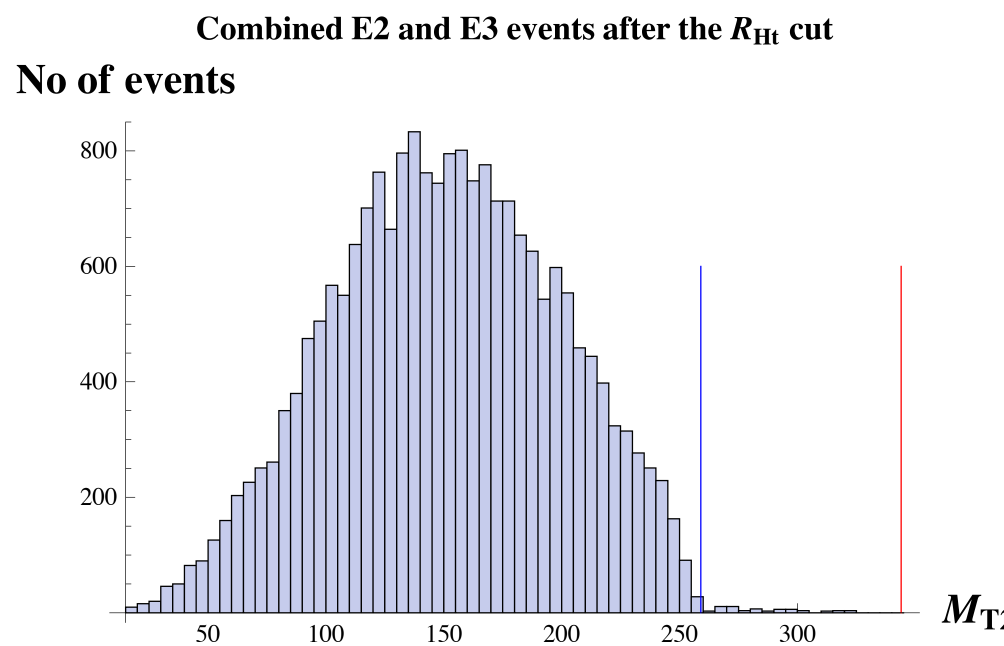
$$H_t^i = \sum_a |P_t^{v_a^i}|$$

$$R_{H_t} = \frac{H_t^{\max}}{H_t^{\min}}$$

$$H_t^{\max} = \max(H_t^1, H_t^2)$$
$$H_t^{min} = \min(H_t^1, H_t^2)$$

"Non-parity" Signal



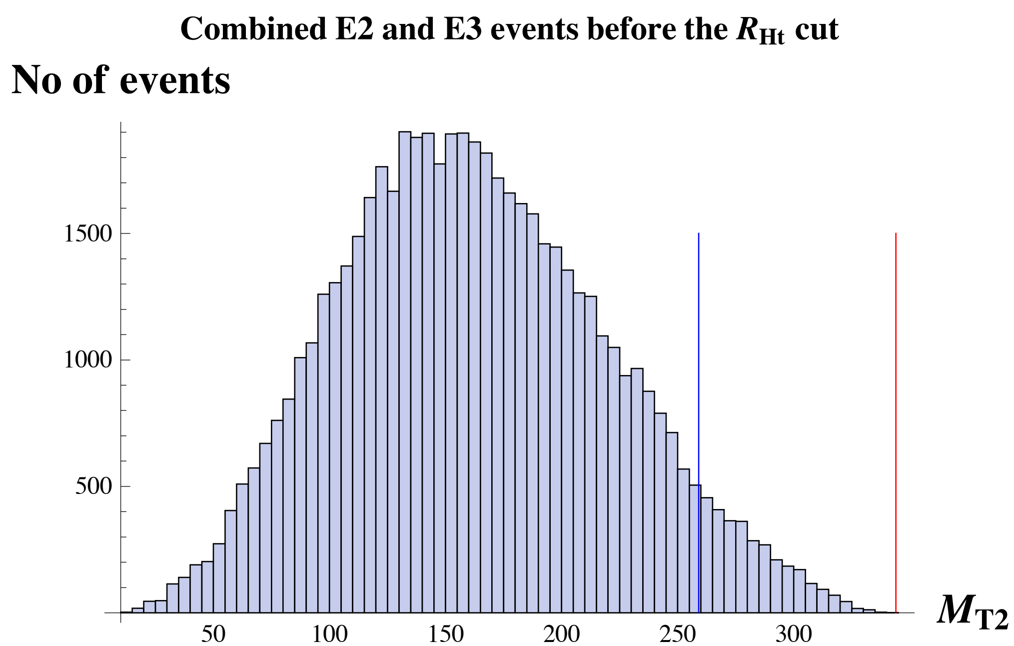


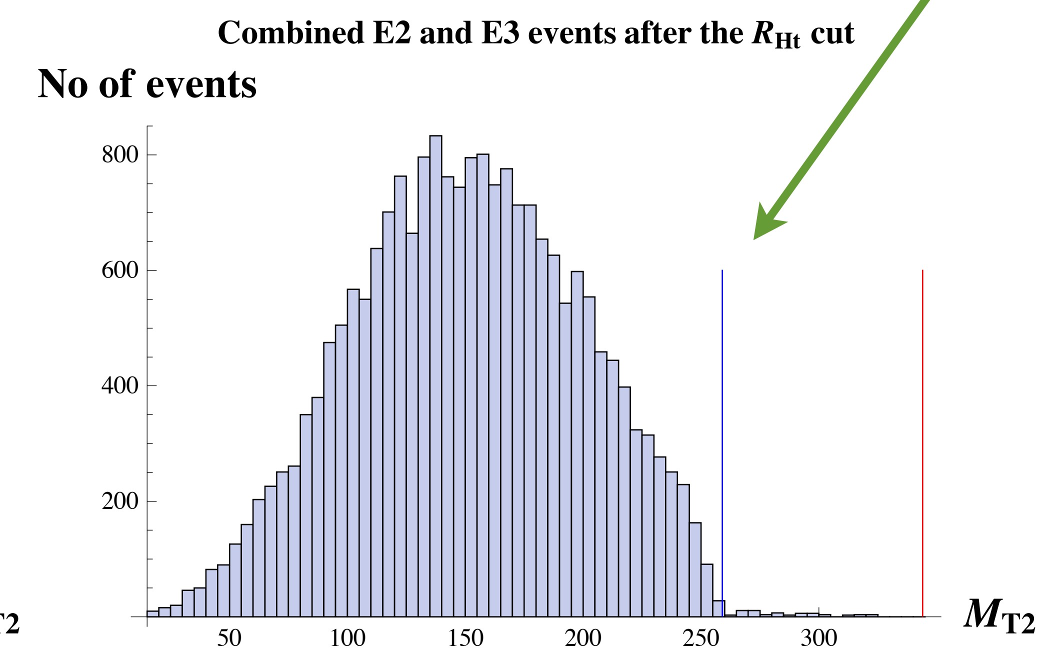
(Mother/DM mass of 400/150 GeV)

(Ht > 5/Trial mass of 9 GeV)

“Non-parity” Signal

MT2 predicted upper edge for three DM in event





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"Non-parity" Signal

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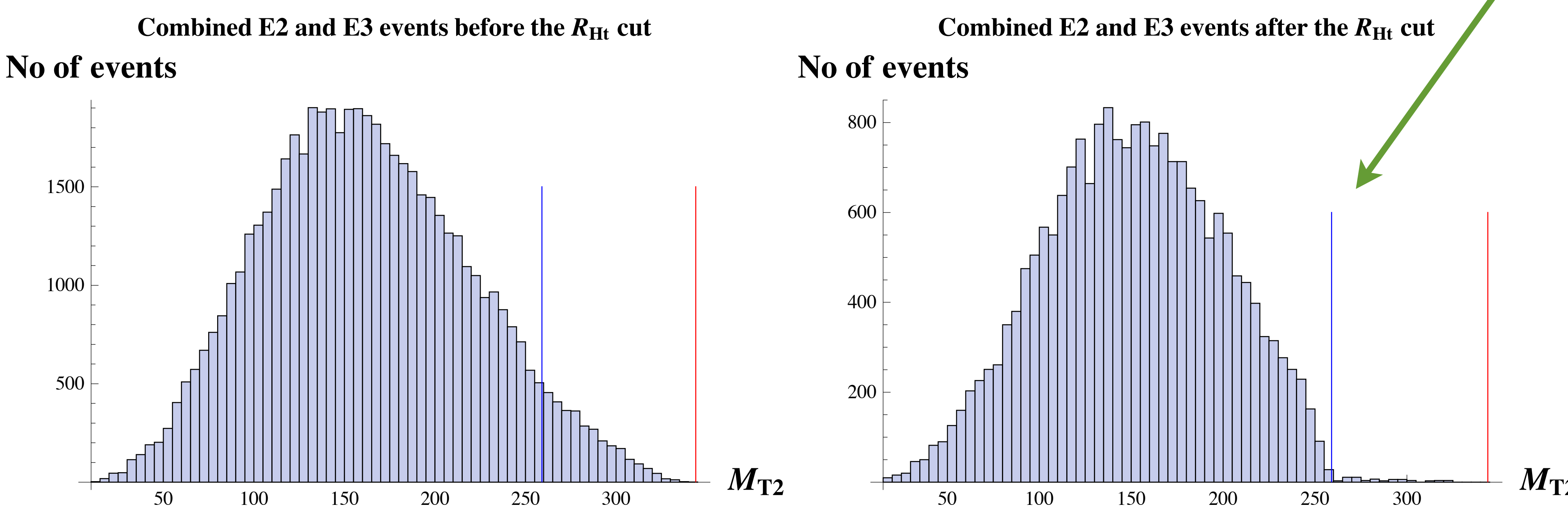

(Mother/DM mass of 400/150 GeV)

(Ht > 5/Trial mass of 9 GeV)

MT2 predicted upper edge for two DM in event

Part III: Signatures with Metastable Particles

What is a Meta-Stable Particle?

- Do not decay in the LHC's detectors.
- Charged under the SM and dark matter stabilization symmetry.
- Lifetime consistent with known bounds.*

* Perl, Kim Halyo, Lee, Lee, Loomba and Lackner,
  Int. J. Mod. Phys. A16 2137 (2001).

Key Points

- Signal: Final states with two meta-stable particles plus large missing energy at the LHC.

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- Claim: Models with parity stabilized dark matter are generally suppressed and distinguishable from models with "non-parity" dark matter.

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- Signal: Final states with two meta-stable particles plus large missing energy at the LHC.

- Claim: Models with parity stabilized dark matter are <u>generally</u> suppressed and distinguishable from models with "non-parity" dark matter.

- Strategy: Focus on parity stabilized models to see the differences.

Simple Claim Again...

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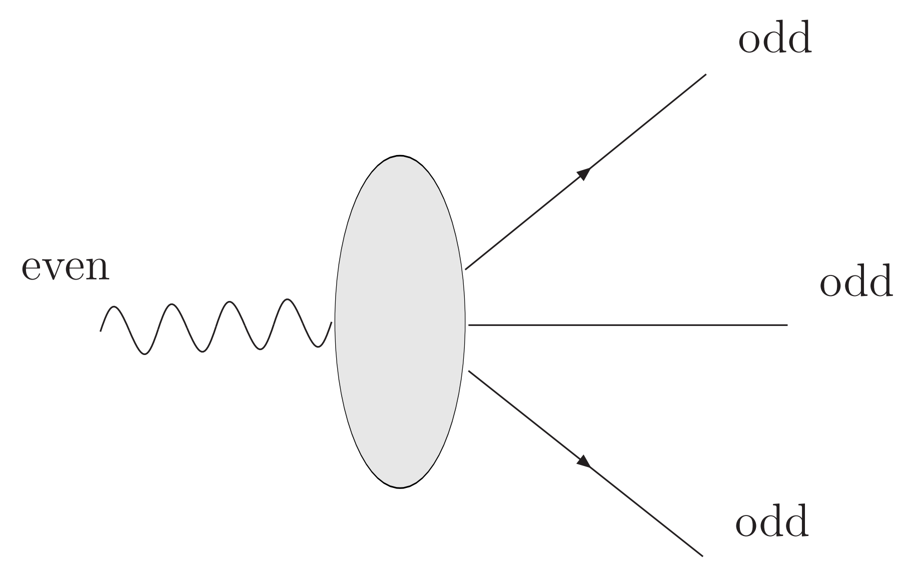
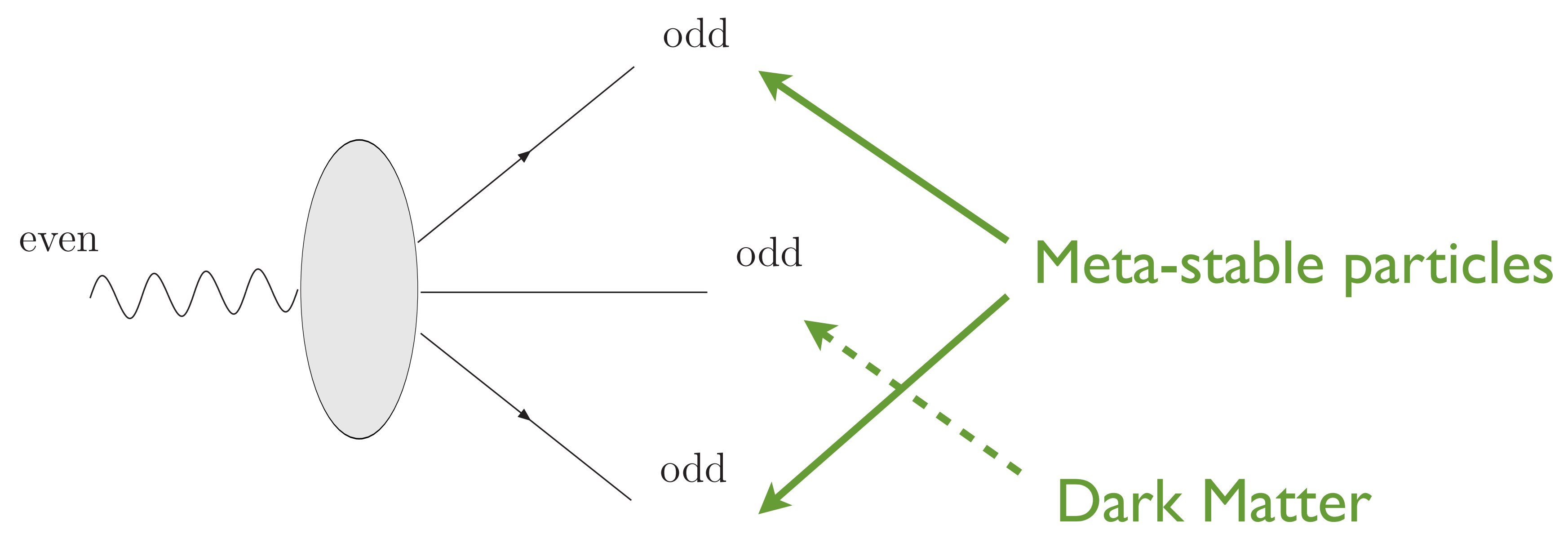
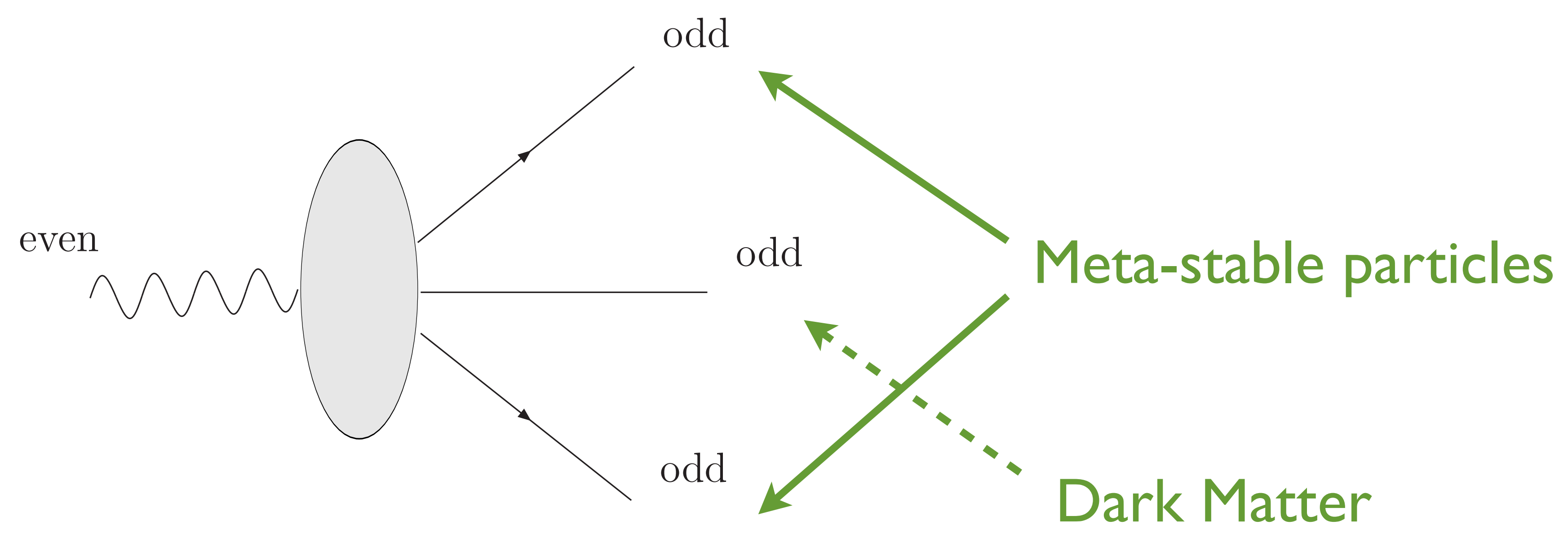


Simple Claim Again...

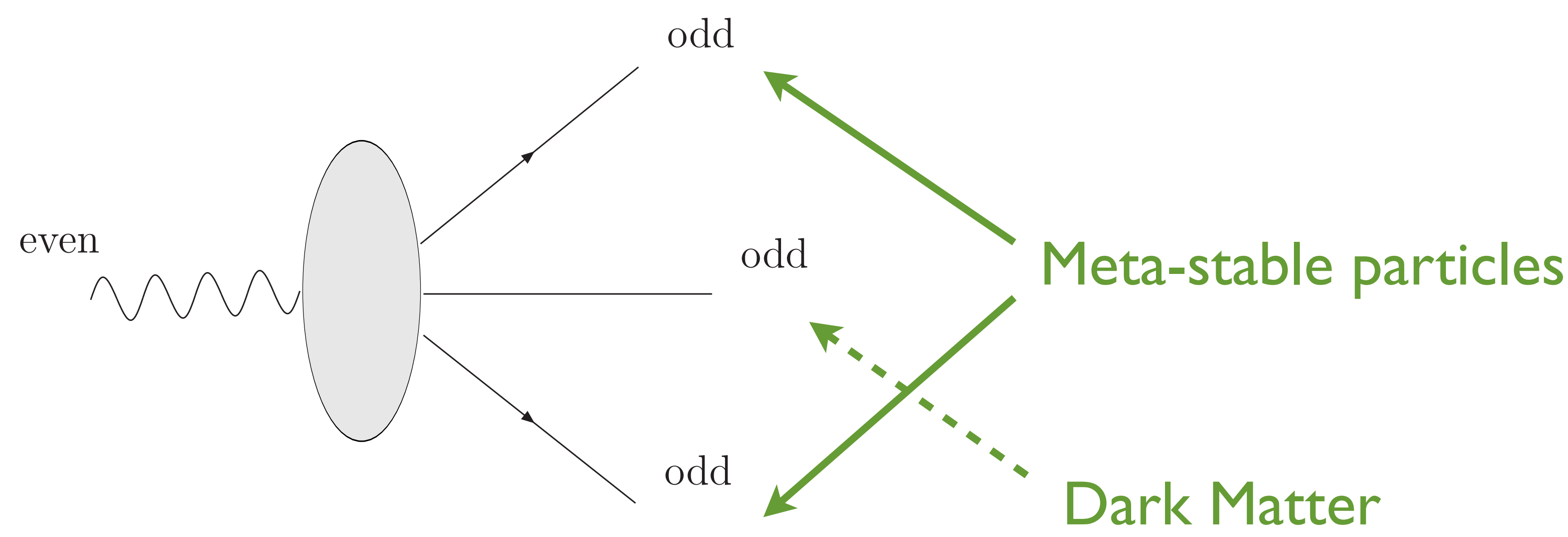


Simple Claim Again...



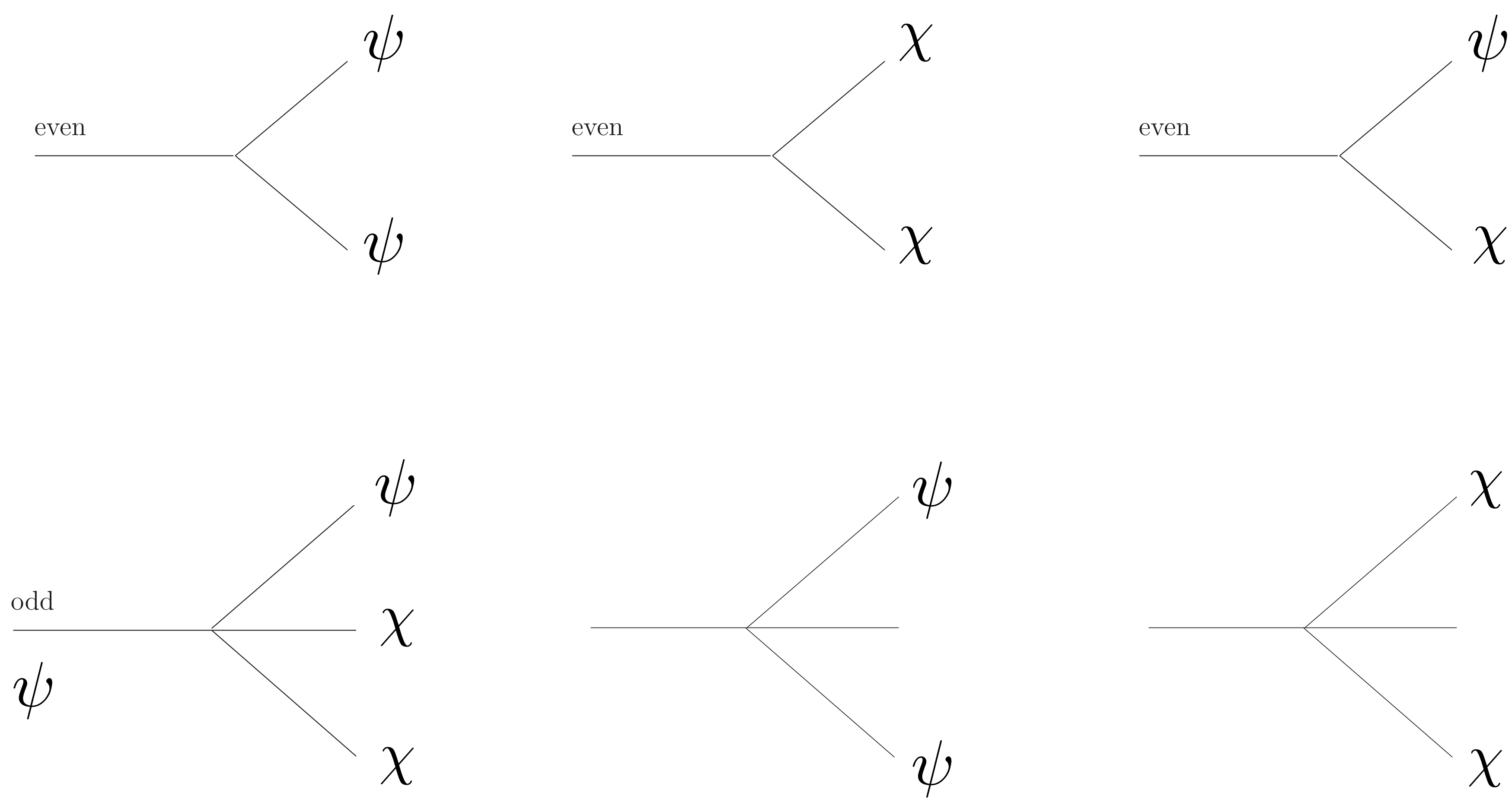
- Diagram rarely happens even for final states with two metastable particles plus an even number of DM.

Simple Claim Again...

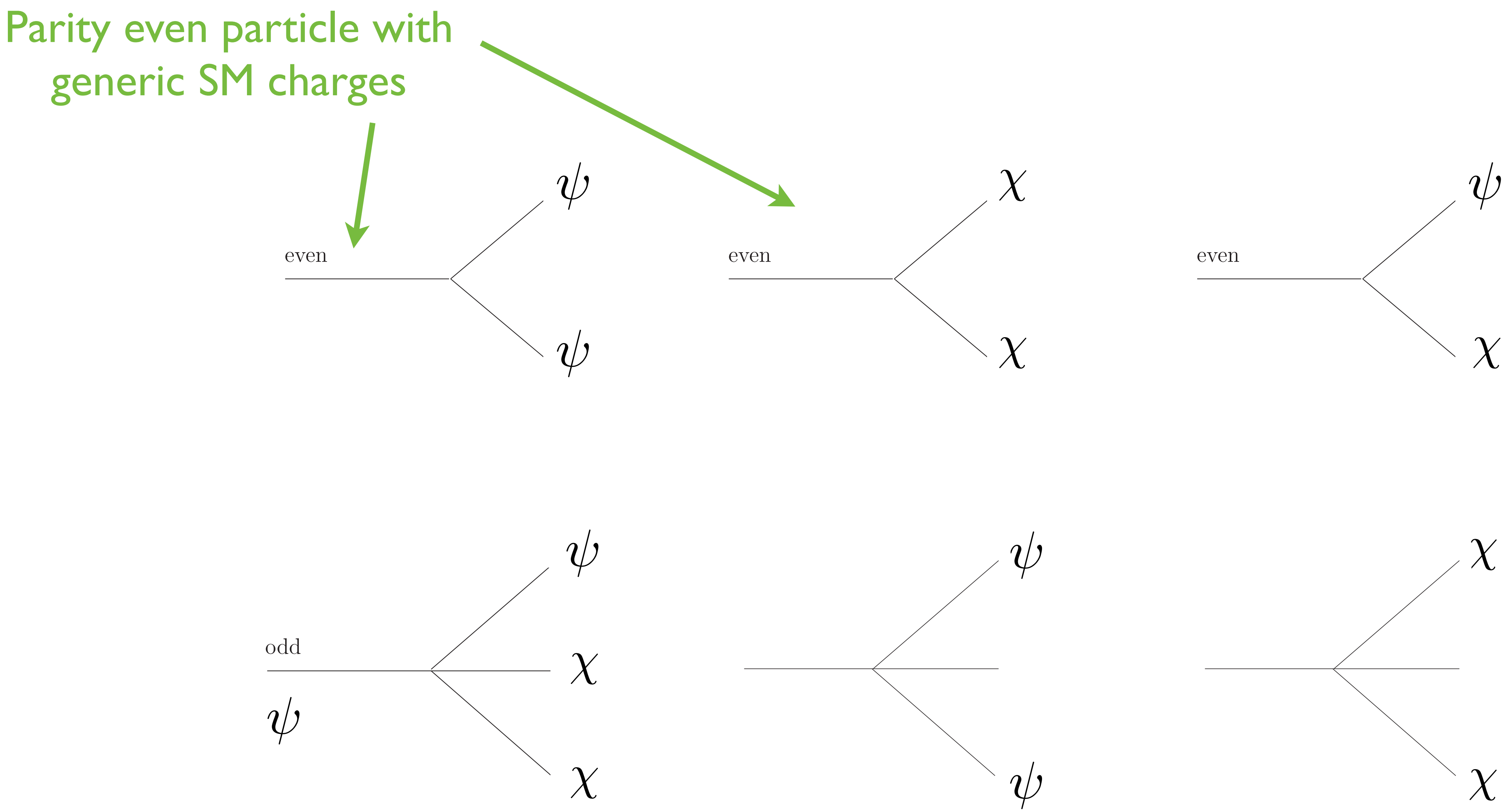


- Diagram rarely happens even for final states with two metastable particles plus an even number of DM.
- Add new particles to prove this...

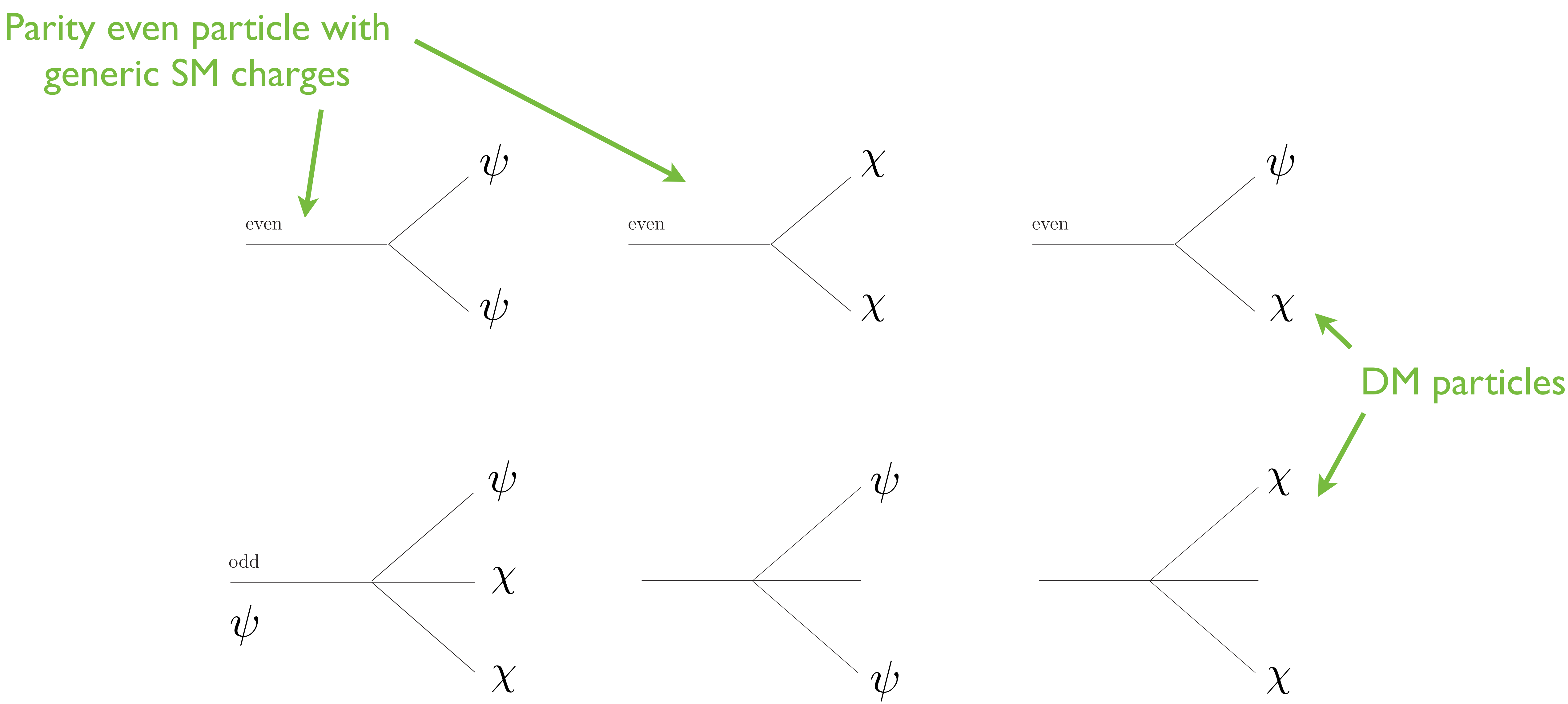
All Possible Relevant Couplings



All Possible Relevant Couplings

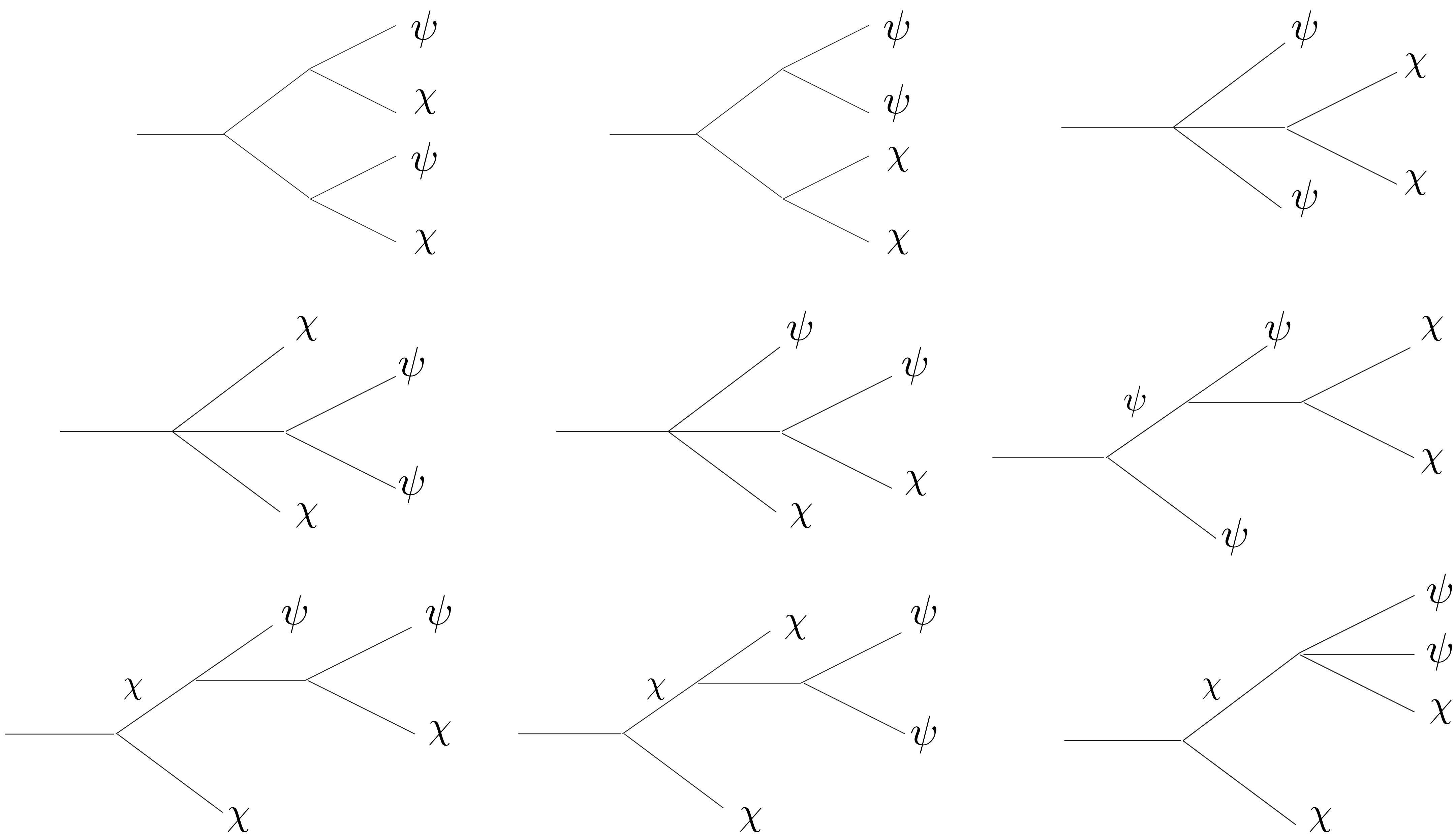


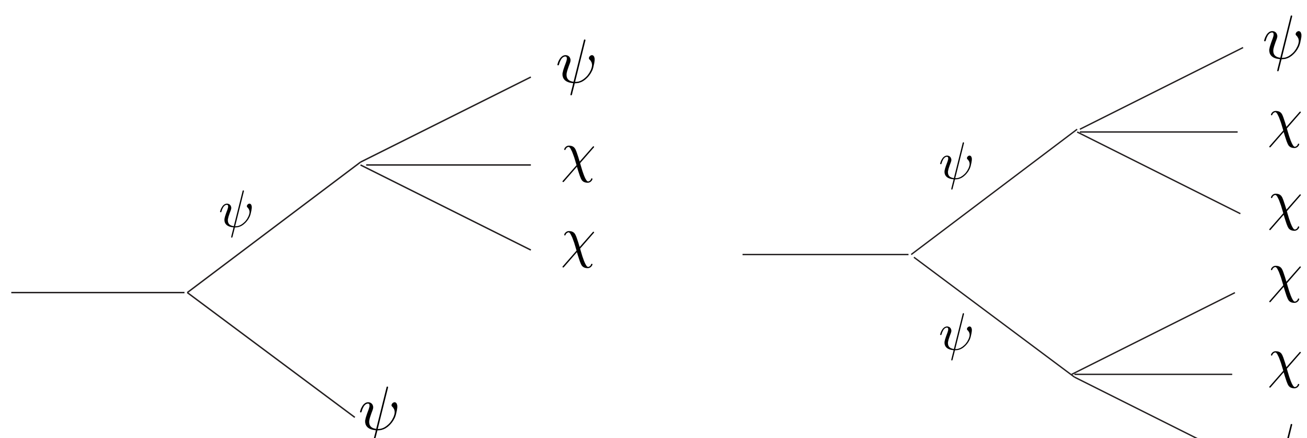
All Possible Relevant Couplings



All Possible Four Body States

(that generate two meta-stable particles + missing energy)

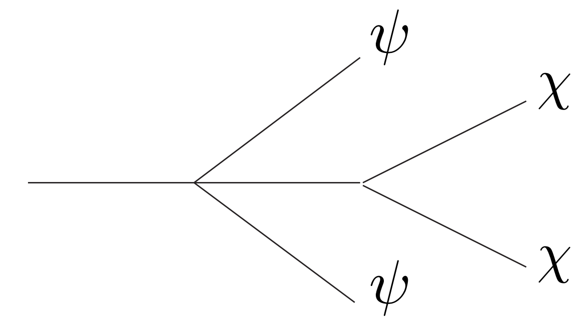




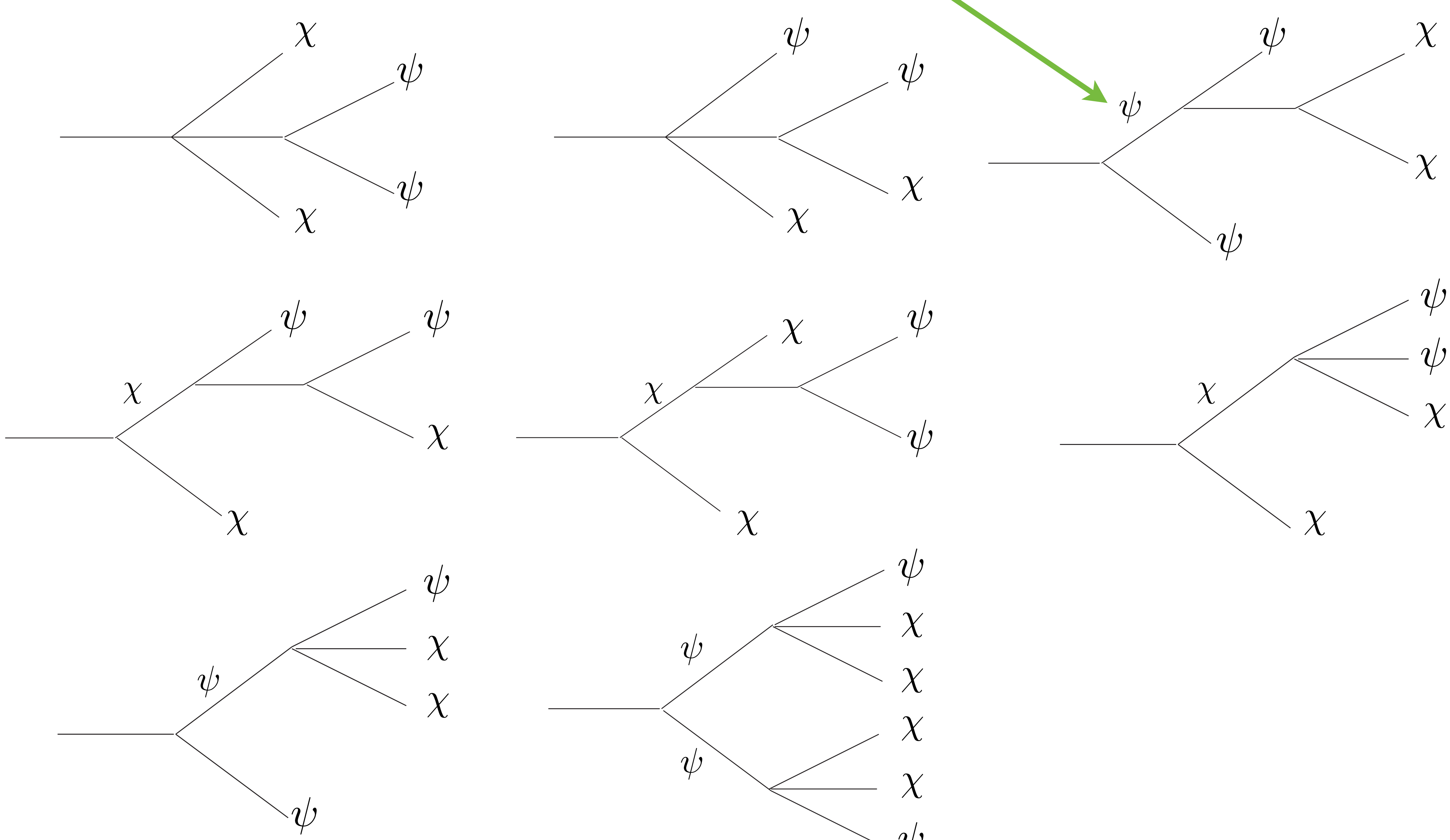
- Could not fit all diagrams on the page if all SM charges were listed.

Off Shell Suppression

All of these diagrams have off-shell suppression...



Consider 500 GeV ψ and a 100 GeV χ.
This particle must go off-shell by a O(0.01) factor or less.



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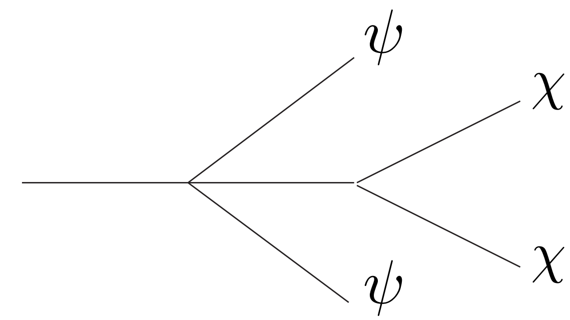
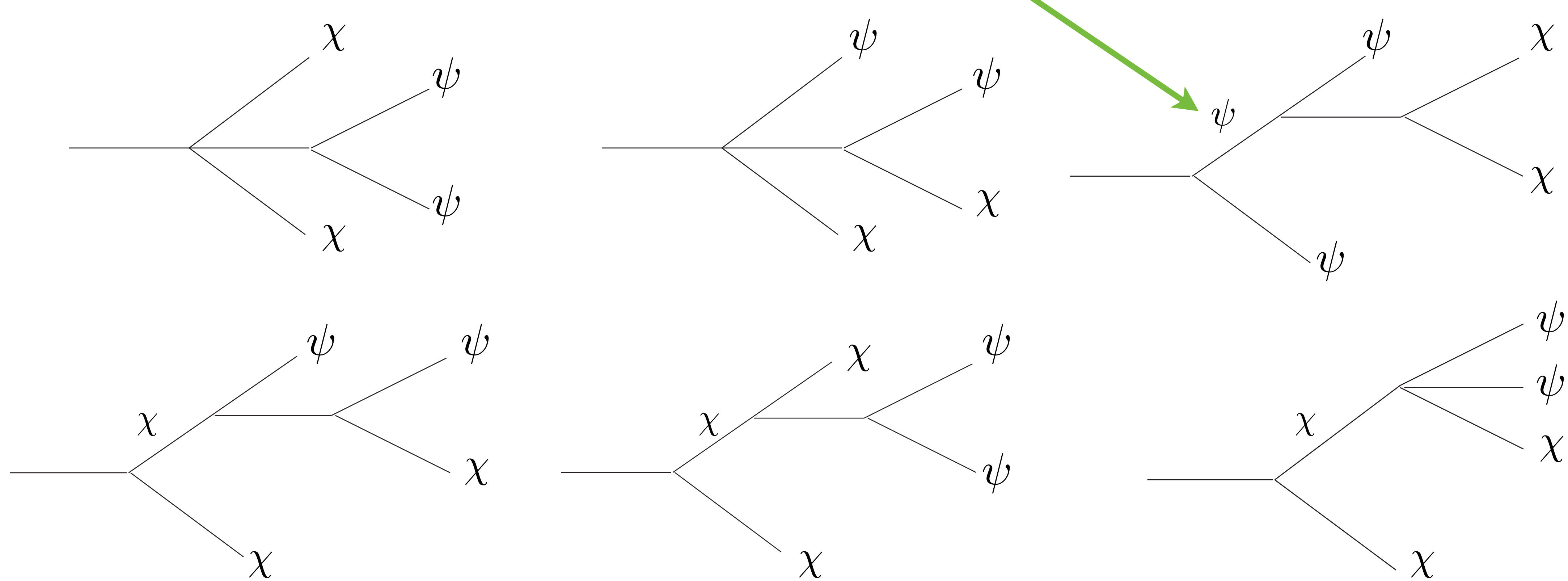
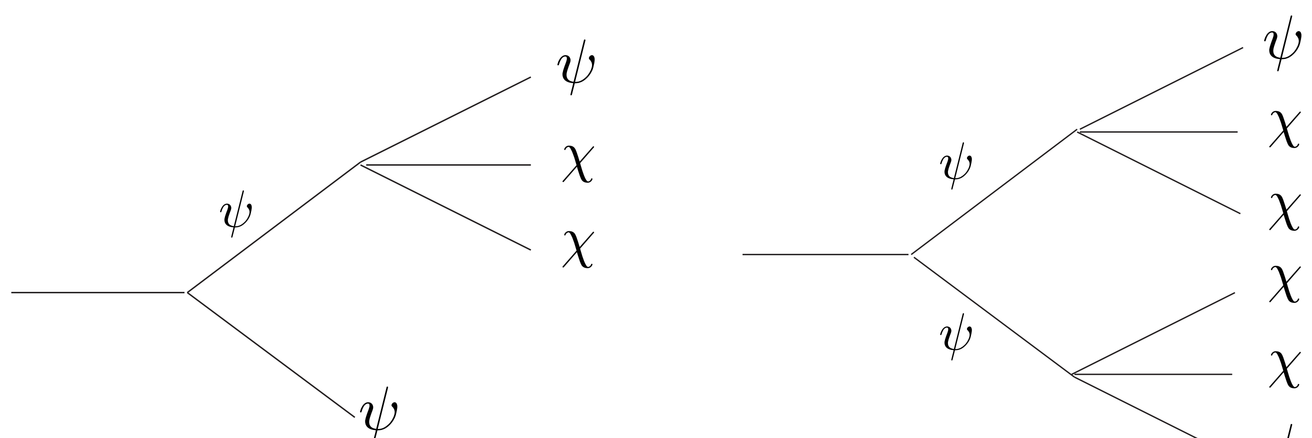
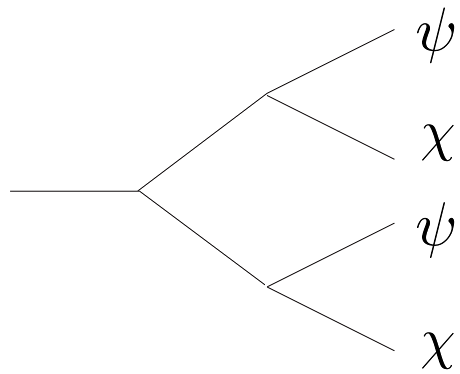


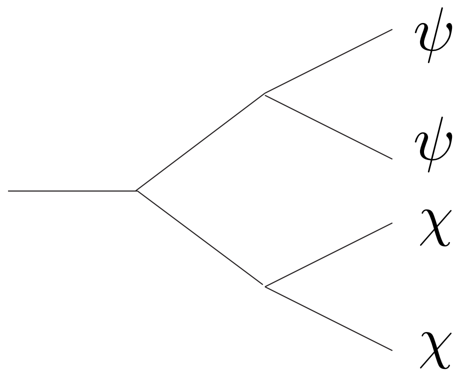




- Strong Suppression Constraint

Remaining Diagrams

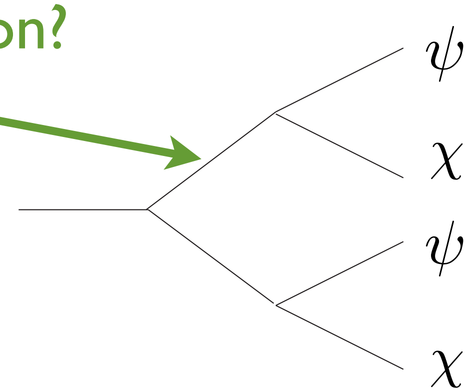


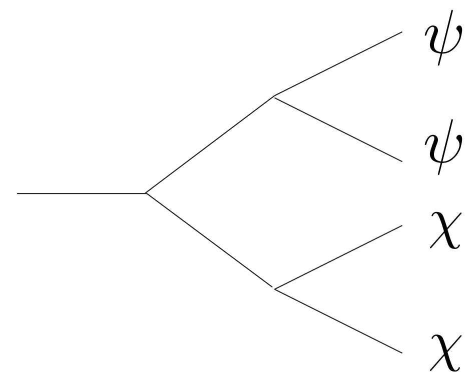


- Constraints on the remaining diagrams?

Remaining Diagrams?

Branching Fraction Suppression?





- An example: Virtual SM higgs particle. Decay rate

$$\Gamma_{h_0 \to \chi\chi \text{ scalar}} = \frac{\kappa_1^2 \, v_{ew}^2}{16\pi m_{h_0}} \sqrt{1 - 4m_\chi^2/m_{h_0}^2}$$

$$\Gamma_{h_0 \to \chi\chi \text{ fermion}} = \frac{A \, \kappa_2^2 \, m_{h_0}}{32\pi} \left(1 - 4m_\chi^2/m_{h_0}^2\right)^{3/2}$$

1 TeV SM higgs branching fraction ~ O(0.01)%
350 GeV higgs branching ~ O(1)% (largest possible)

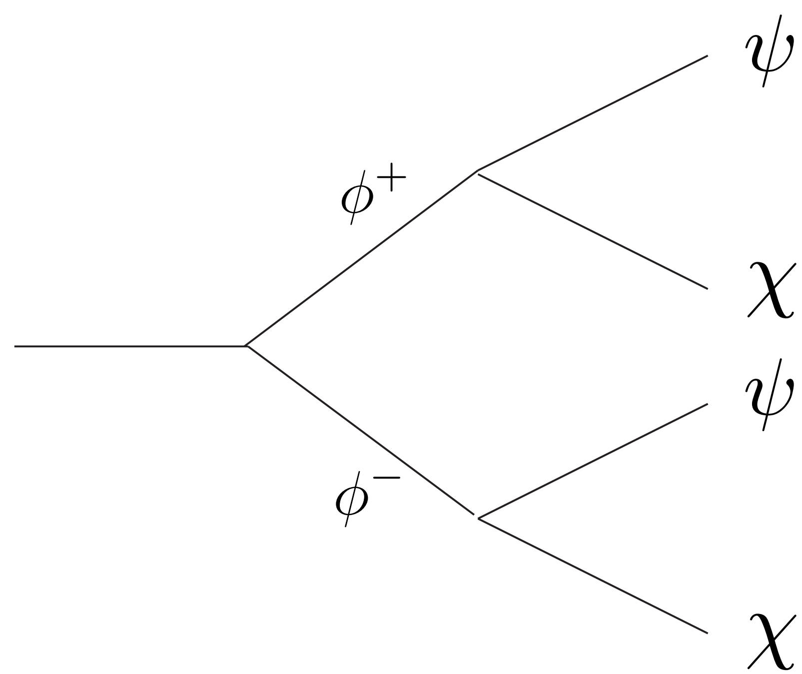
Remaining Diagrams Suppressed?

- Arguments are not 100%.

Remaining Diagrams Suppressed?

- Arguments are not 100%.
    - Best we can do? Try to reconstruct the new scalar to see if it is parity even.

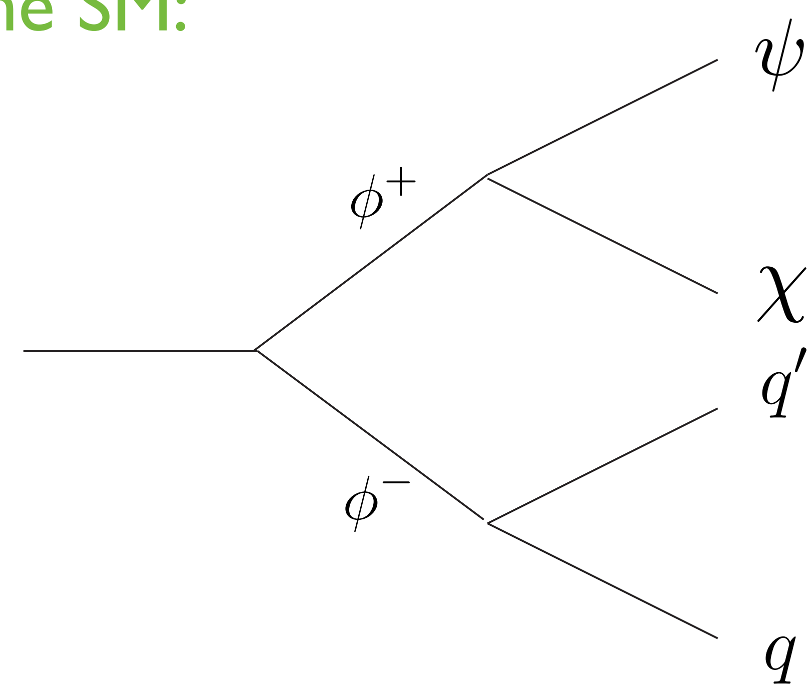
Reconstructing Diagrams



Reconstructing Diagrams

Search for processes where one branch decays into the SM:

$$p\,p \;\longrightarrow\; \psi\,\chi^* + \mathrm{SM}$$



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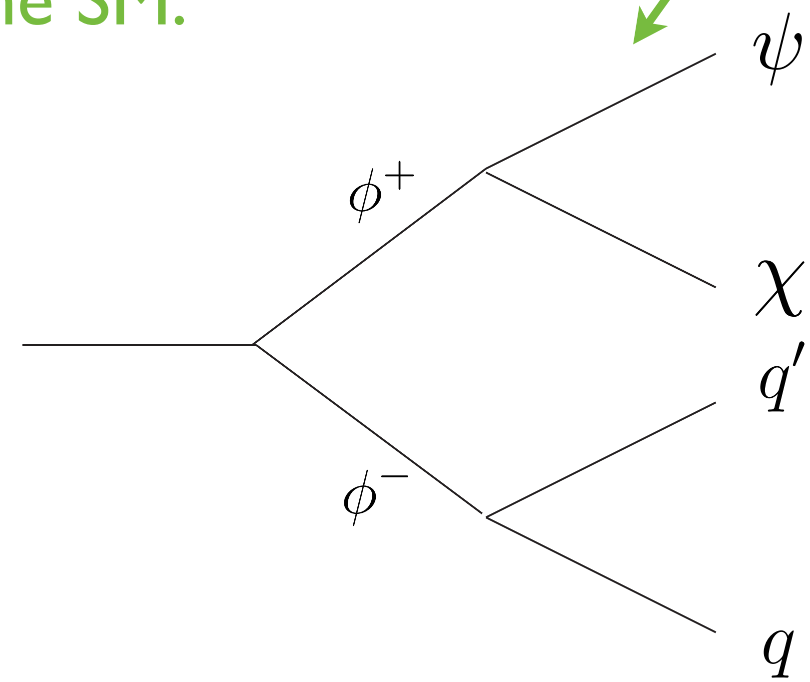
Tag meta-stable to reduce background



Reconstruct charged higgs mass

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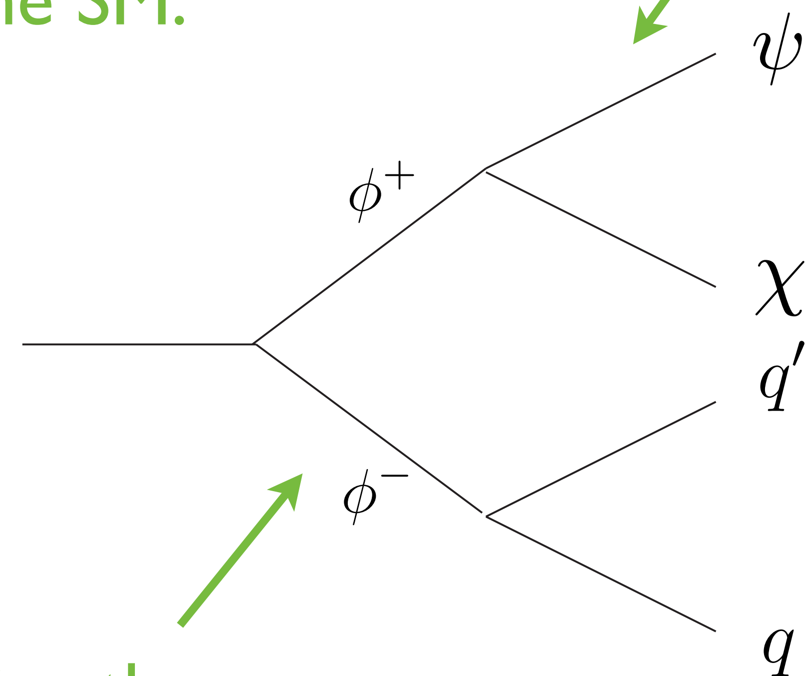

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Reconstructing the mass gives us a “tag” and verifies this is parity even.

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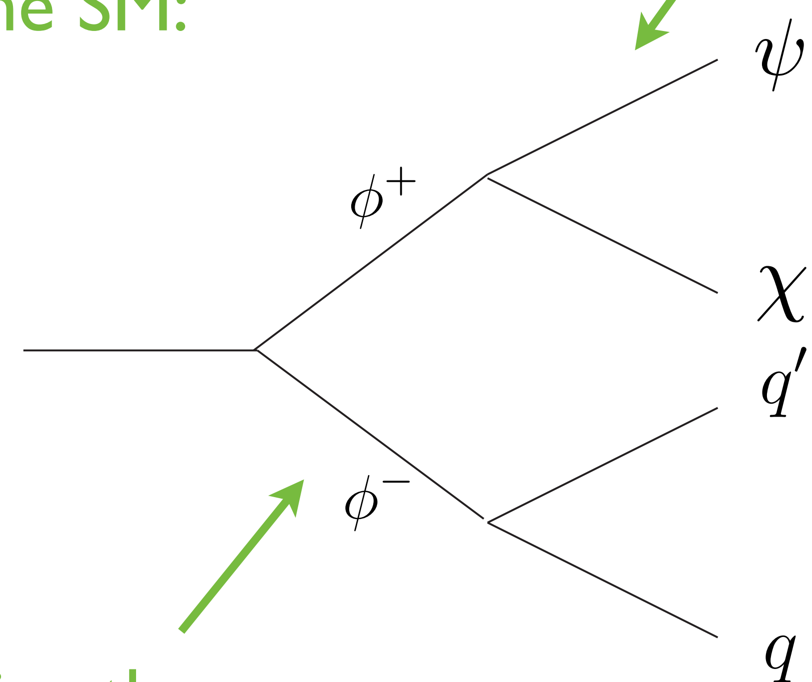
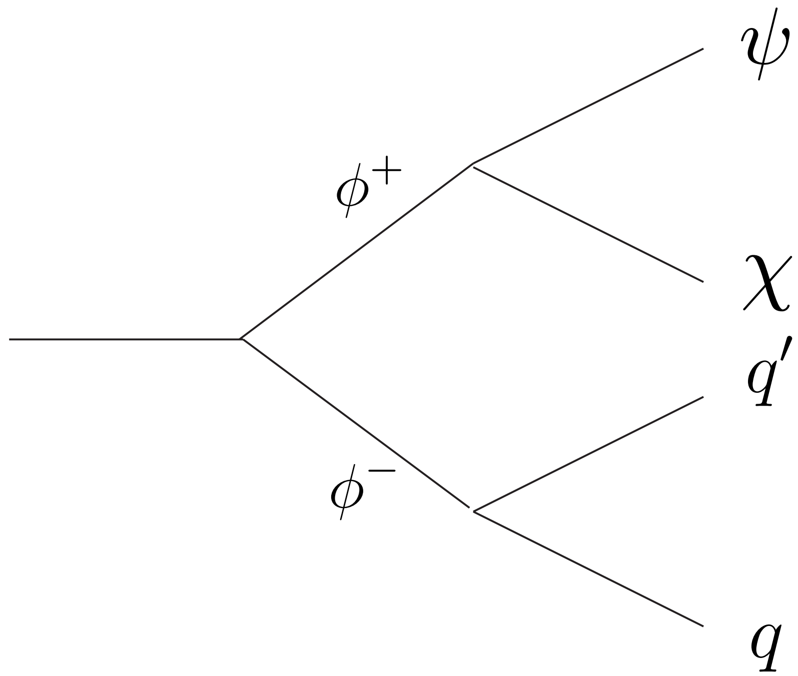


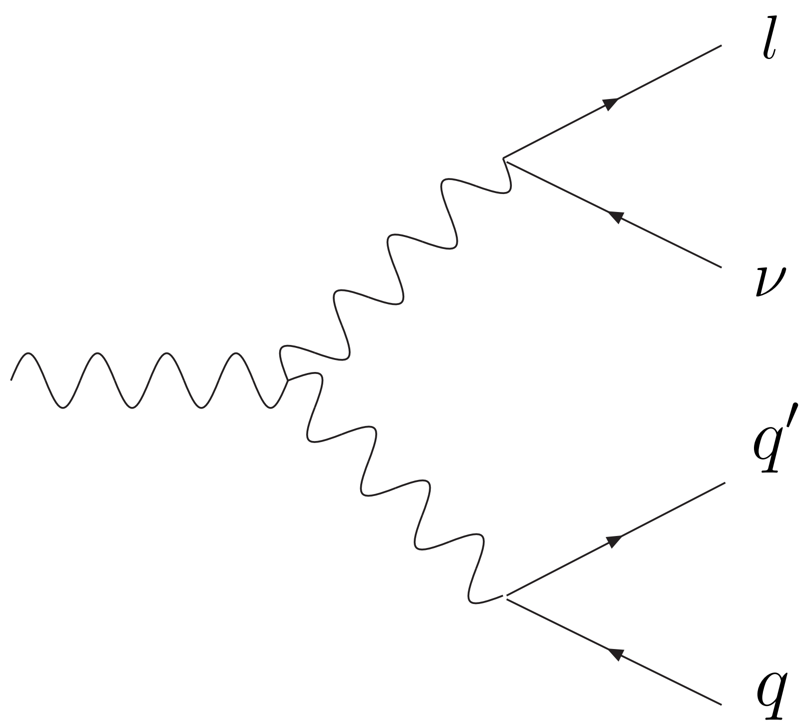
Reconstruct charged higgs mass

Reconstructing the mass gives us a "tag" and verifies this is parity even.

- Reconstruct in analogy to WW reconstruction to get the mass of ϕ^+.

Reconstructing Diagrams





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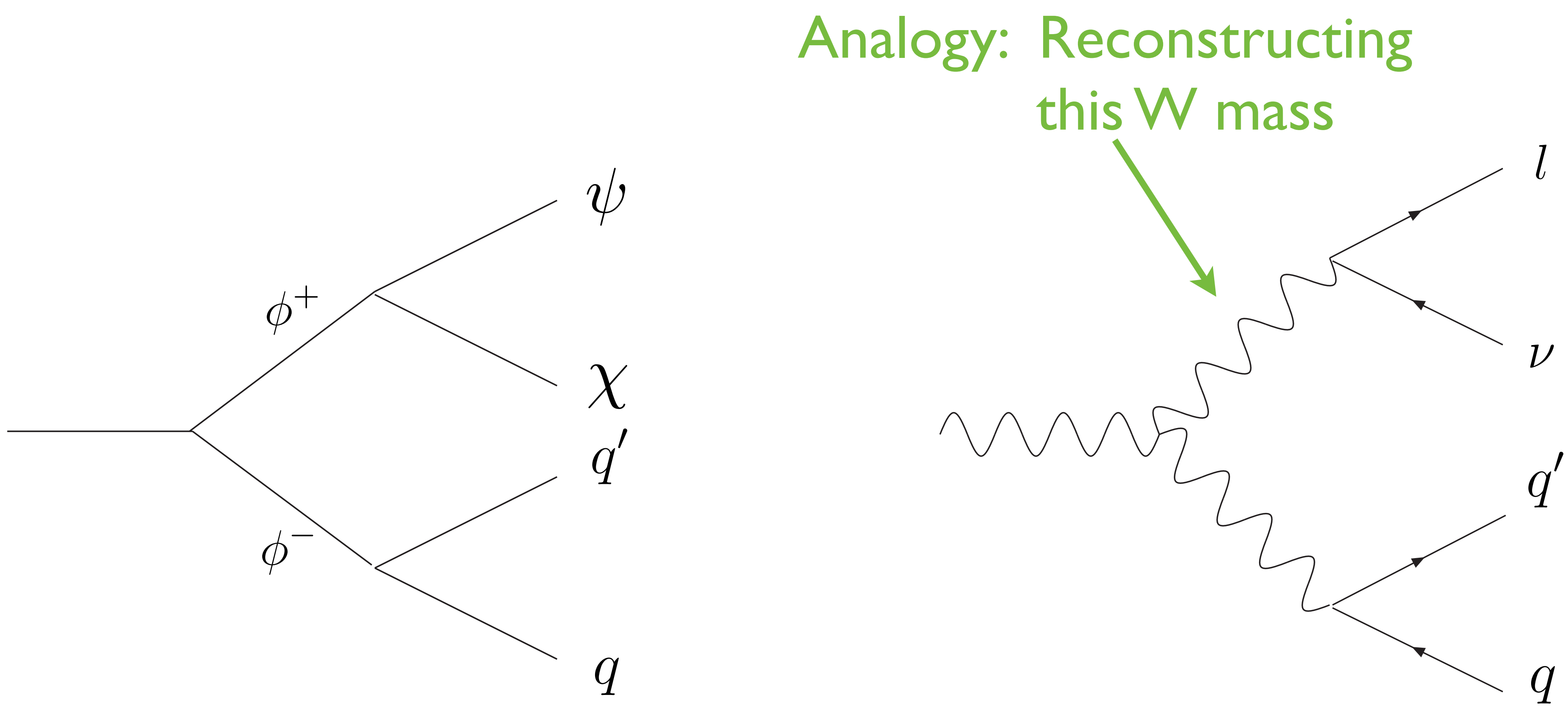
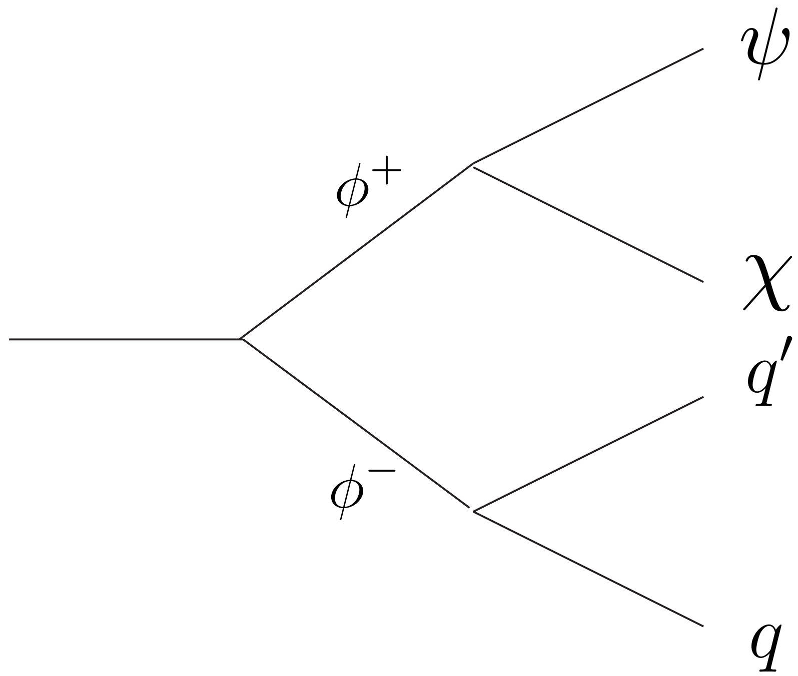
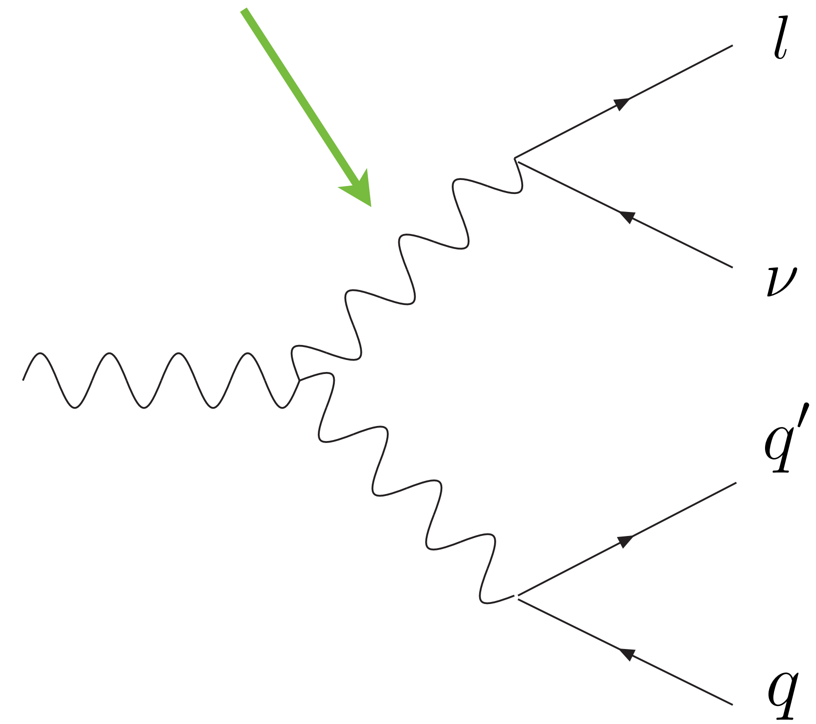


Reconstructing Diagrams



Analogy: Reconstructing this W mass

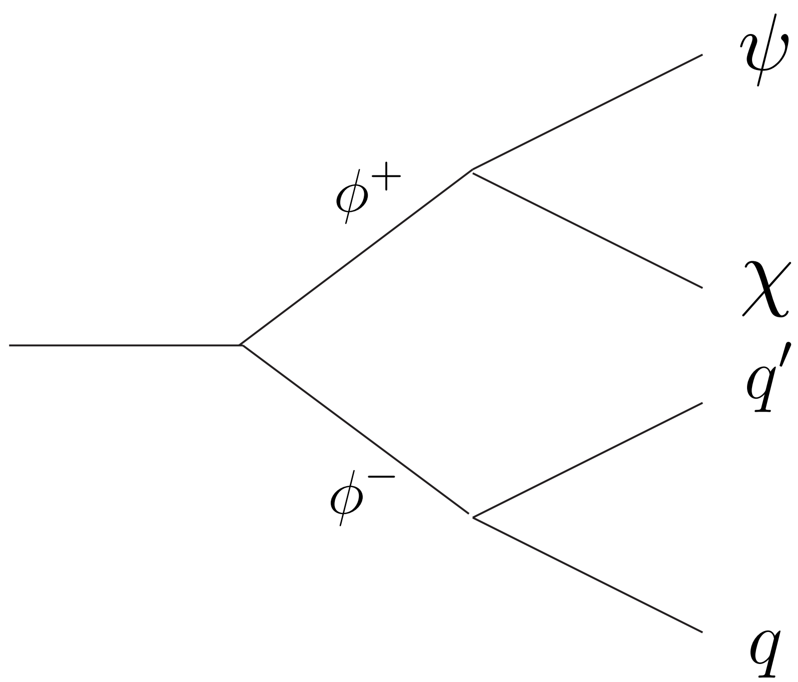


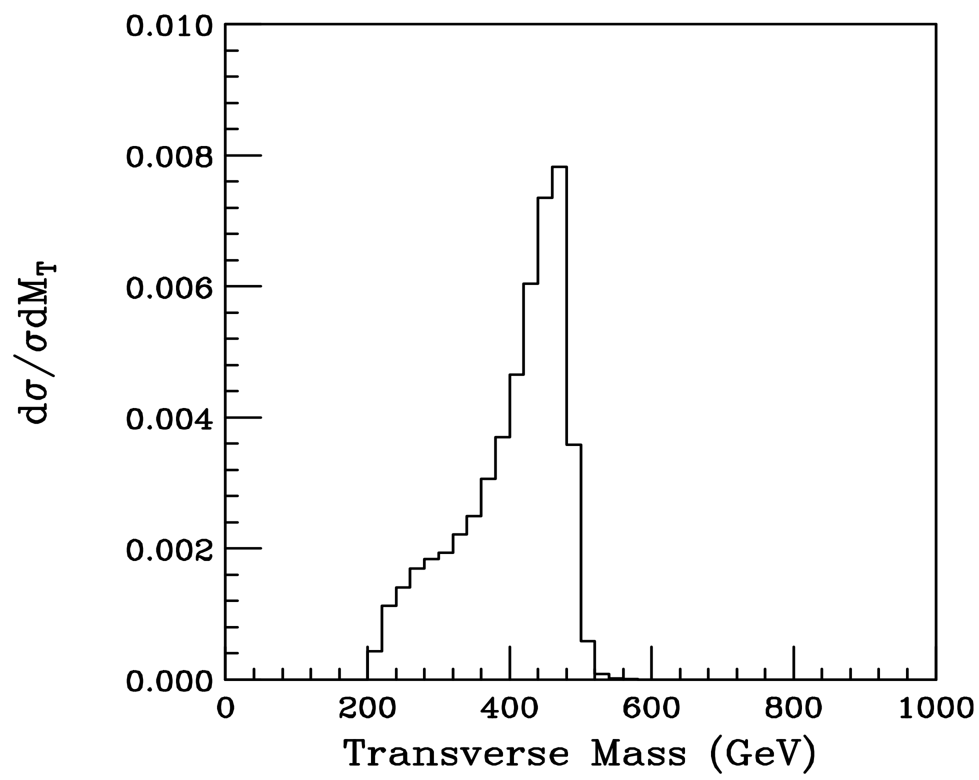
- Define variables: $M_T = \sqrt{(E_T + \not{E}_T)^2 - (\vec{p}_T + \not{\vec{p}}_T)^2}$

$$E_T^2 = \vec{p}_T^2 + M_\psi^2$$

$$\not{E}_T^2 = \not{\vec{p}}_T^{\,2} \qquad \not{\vec{p}}_T = \sum \vec{p}_{T\ \mathrm{visible}}$$

Reconstructing Diagrams





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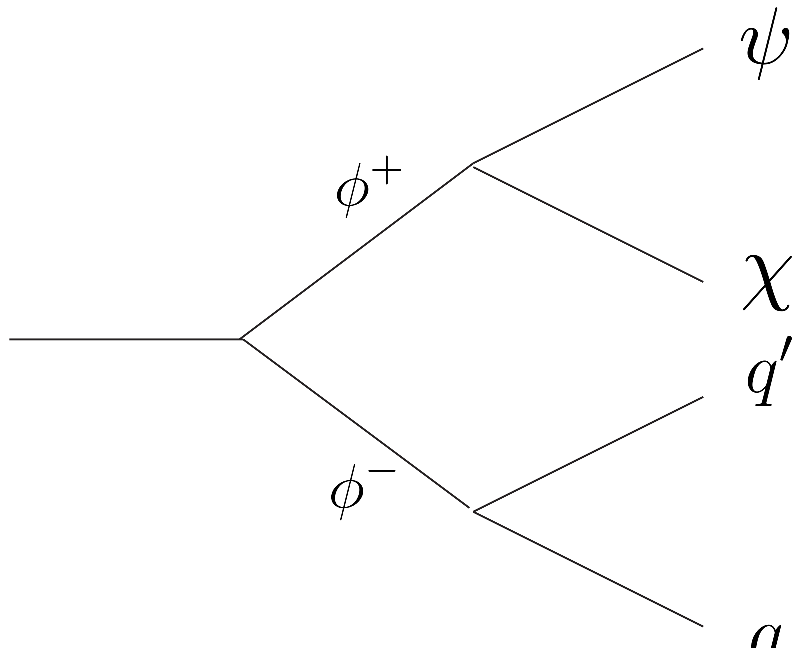
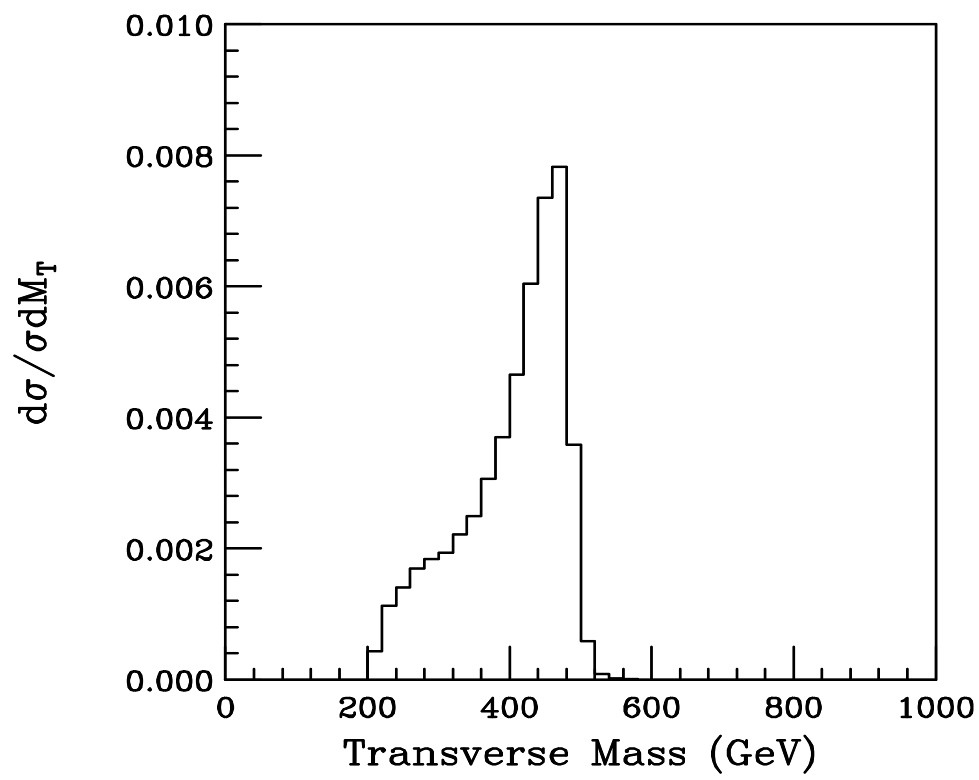
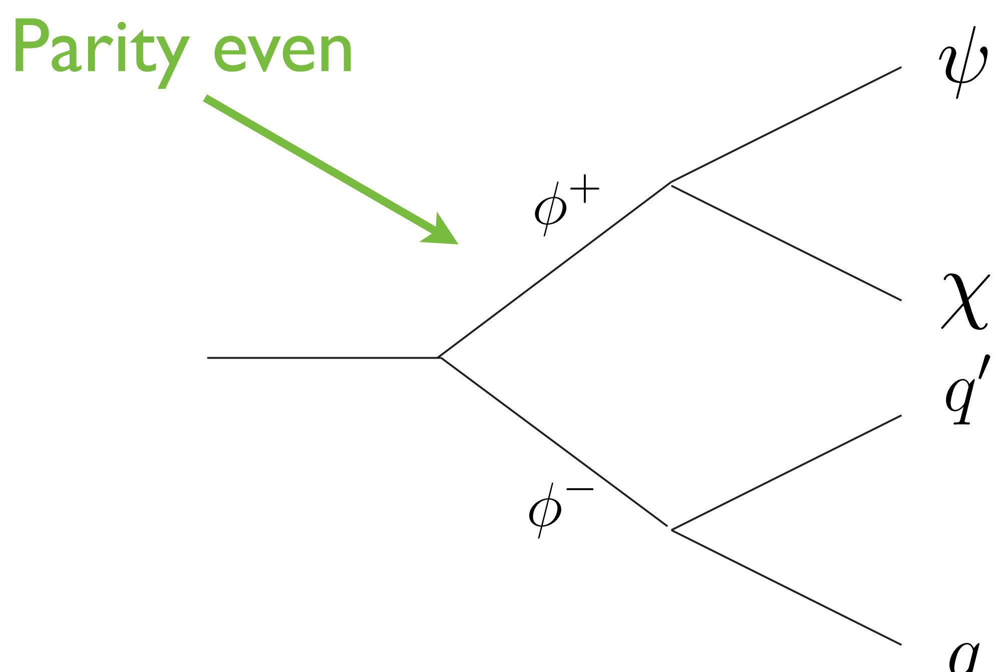
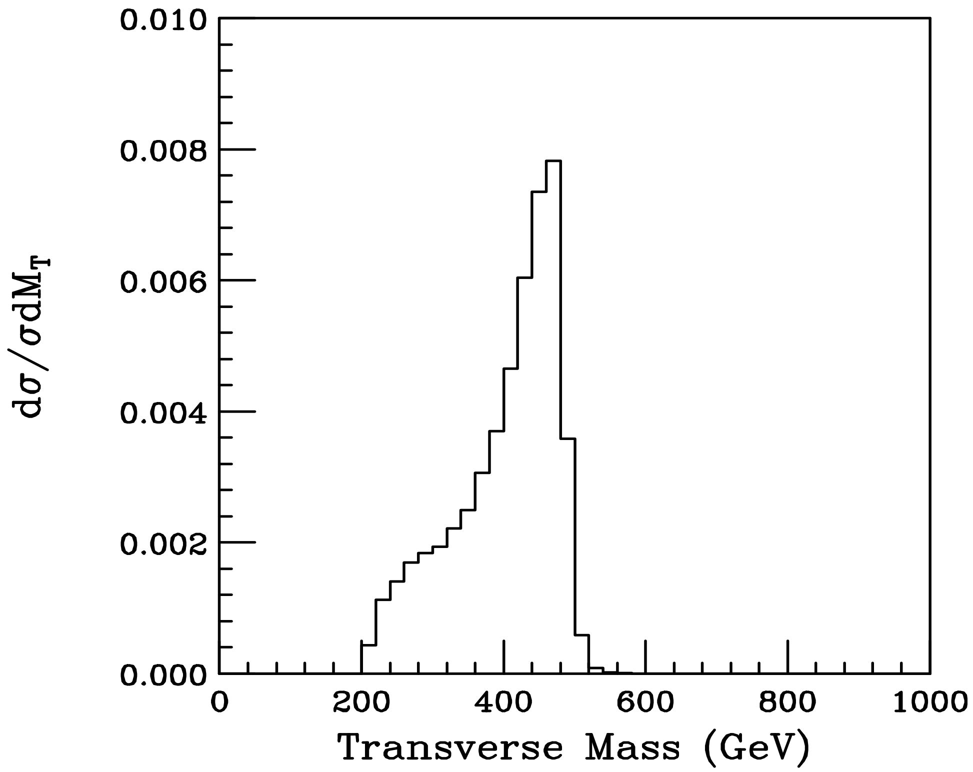




- 500 GeV ϕ, 200 GeV ψ and 100 GeV DM χ.

Reconstructing Diagrams

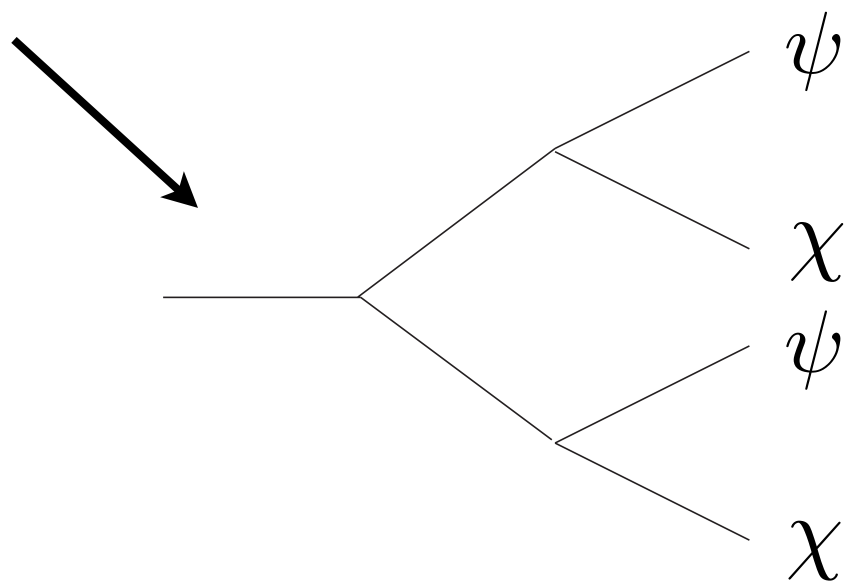




- 500 GeV ϕ, 200 GeV ψ and 100 GeV DM χ .
- Conclusion: Parity even scalar is generating signal.

Going Forward

- We assume no scalars in our EFT which mediate processes like



- Onto collider studies . . .

Model Parameters

- Take masses of the meta-stable particles to be

$$m_\psi = 300,\ 600\ \mathrm{GeV}$$

- All dark matter candidates are

$$m_\chi = 100\ \mathrm{GeV}$$

Backgrounds

- Many SM process produce a potential background: light quark production (QCD), bbbar, ttbar, W, Z, WW and ZZ.
- Any SUSY process with final state neutrinos.
- ATLAS and CMS have unique approaches to eliminate the backgrounds.

An Additional SM Background

- SM can produce a similar missing energy process by radiating off a Z boson:

$$p\,p \to Q\,\overline{Q}\,Z \to Q\,\overline{Q}\,\nu\,\overline{\nu} \qquad\qquad q\,\bar{q} \to L\,\overline{L}\,Z \to L\,\overline{L}\,\nu\,\overline{\nu}$$

Important the signal cross section is no less than 10% of the SM background (conservatively) to preclude statistical fluctuations

An Additional SM Background

- Some numbers: (with 300 GeV "hadron" no cuts)
  - Cross section to radiate off a Z from heavy stable quarks and decay invisibly: 0.33 pb x 0.2 = 0.07 pb.
  - Cross section to radiate off a 100 GeV heavy gauge boson: 0.28 pb.
  - Cross section to radiate off a 275 GeV heavy gauge boson: 0.01 pb.
- No problem with this background.

ATLAS Cuts

- ATLAS requires the "muon tracks" to have a transverse momentum of $p_T > 135\ \mathrm{GeV}$ for a 300 GeV "hadron."
- The events are restricted to the "triggerable" part of the muon detector $|\eta| \leq 2.4$.
- No jet in the inner detector must come within a cone of $\Delta R =< 0.4$ of the "muon track."
- The "muon tracks" must have a velocity between $0.7 < \beta_{\mathrm{ATLAS}} < 0.9$.

*See, for example, hep-ex/05011014

CMS Cuts

- CMS detector muon detector is partly suspended by iron yoke.

  The “hadrons” can charge flip even in the muon detector.

- The collaboration requires a highly ionizing track in the inner detector.

- The analysis: Kept events with charged “hadrons” in the inner detector.

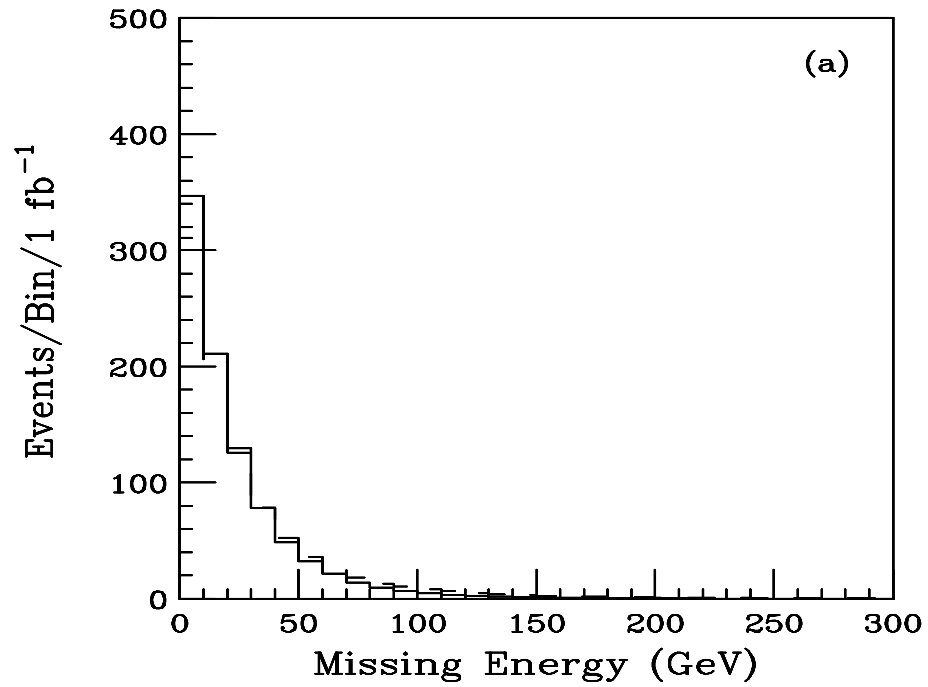
CMS Cuts*

- CMS require an invariant mass of $m > 100\ \mathrm{GeV}$.
- CMS requires the "muon tracks" to have a velocity of $0.45 < \beta_{\mathrm{CMS}} < 0.8$.
- For these cuts, CMS finds "a background free region."
- Since the S/B is so high, we safely neglect the background.

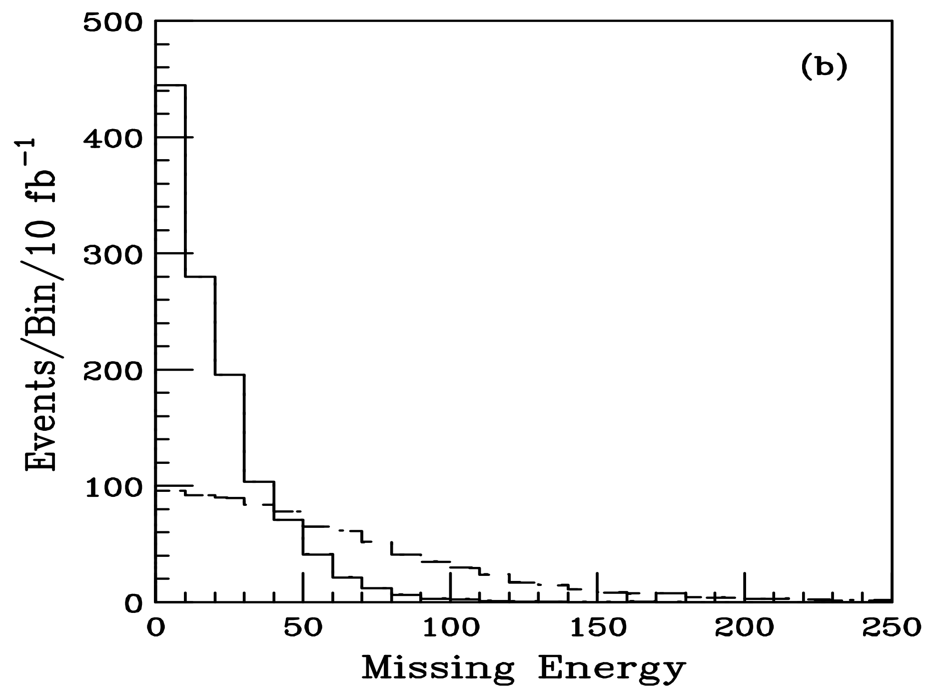
*CMS Collaboration, CMS PAS EXO-08-003

Signal from Acceptance Cuts?

Atlas (solid) and CMS (dotted) for the signal production (chalkboard).



Same plot as above but with ATLAS and CMS cuts.



- To clarify signal we require an additional cut.

"Non-parity" Results

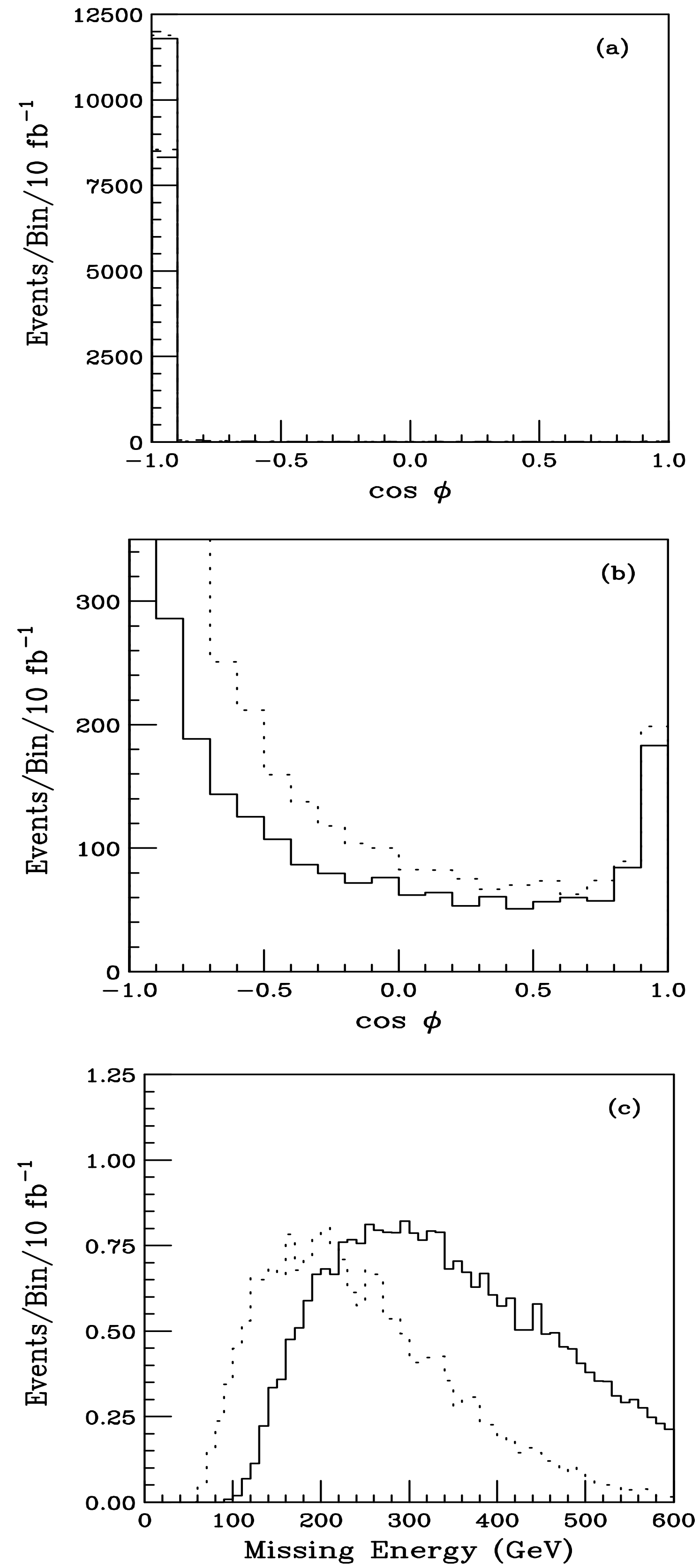
Transverse angle for ATLAS (solid) and CMS(dotted). Most events are back-to-back. All plots use feature 100 GeV DM and 300 GeV meta-stable particles. All kinematic cuts are used.

Same plot as above but emphasizing the non back-to-back events.

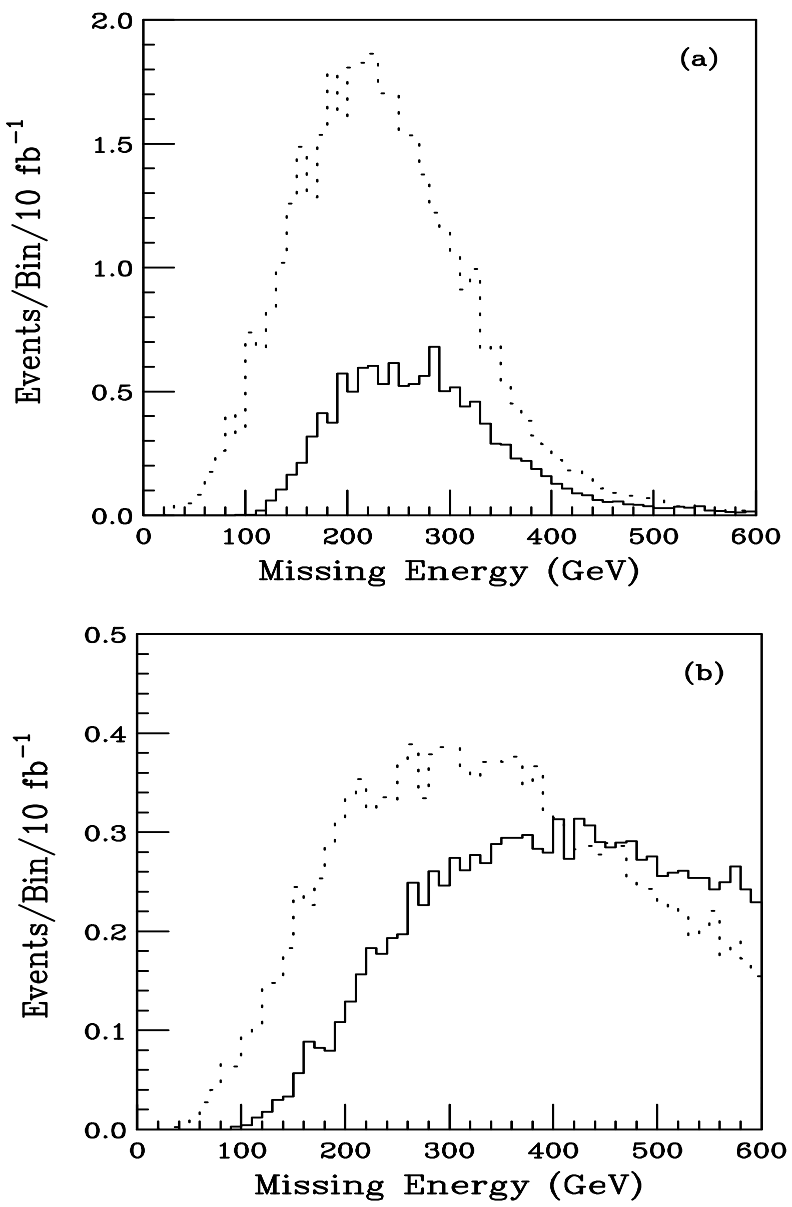
Applying the cut

$$\cos\phi > -0.9.$$

None of the back-to-back events survived. About 70 events of signal for 10 inverse fb.



More Results



Same plots with all cuts for the Agashe-Servant scenario (a) and light hidden sector (b).

Companion Model

	ATLAS		CMS	
	$S/\sqrt{B}$	S/B	$S/\sqrt{B}$	S/B
300 GeV ψ	34.3	4.1	29.4	3.92
600 GeV ψ	10.1	4.1	9.5	4.1

Agashe-Servant

	ATLAS		CMS	
	$S/\sqrt{B}$	S/B	$S/\sqrt{B}$	S/B
300 GeV ψ	34.3	4.1	29.4	3.92

Light Hidden Sectors

	ATLAS		CMS	
	$S/\sqrt{B}$	S/B	$S/\sqrt{B}$	S/B
300 GeV ψ	5.33	0.63	8.76	1.04
600 GeV ψ	0.75	0.30	1.08	0.47

Conclusion/Future Goals

If the LHC is relevant for dark matter hard questions like "what is the stabilization symmetry of dark matter" may be possible.

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If the LHC is relevant for dark matter hard questions like "what is the stabilization symmetry of dark matter" may be possible.

Implement ideas on reconstructing multi-hard jet events with timing.

Look to distinguish strongly coupled hidden sectors from perturbative ones...

Additional Slides

A Simulation

- Need to reliably estimate...
  - How many “hadrons” charge flip to neutral? (Neutral “hadrons” generate obscuring missing energy.)
  - How much missing energy comes with and without emission of massive dark gauge bosons?
  - What are the cross sections?

A Simulation

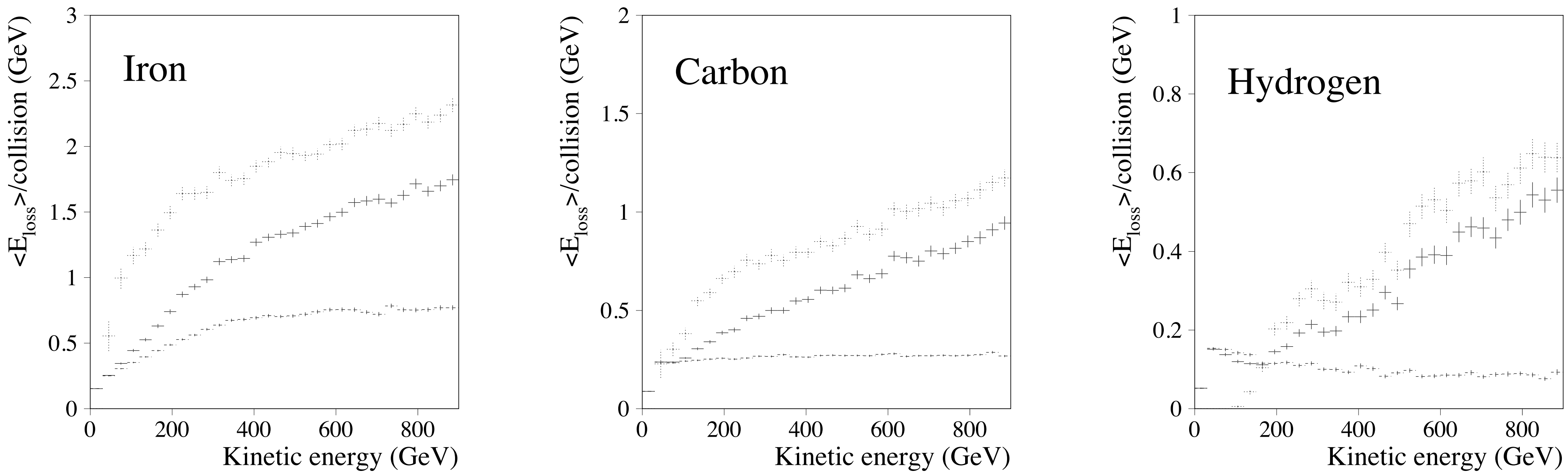
- More things to reliably estimate...
  - How many of the stable particles stop in the detector generating more obscuring missing energy?

    Energy fraction of the exchanged SM quark partons is $\mathcal{O}(0.001)$ of the "hadron" total.* Most interactions are low-energy QCD. Very few "hadrons" are stopped; but need to account for the relatively small signal.
- GEANT4 without introduction is very difficult to use. No access to collaboration software.

*See review, Fairbairn, et al. hep-ph/0611040

A Simulation

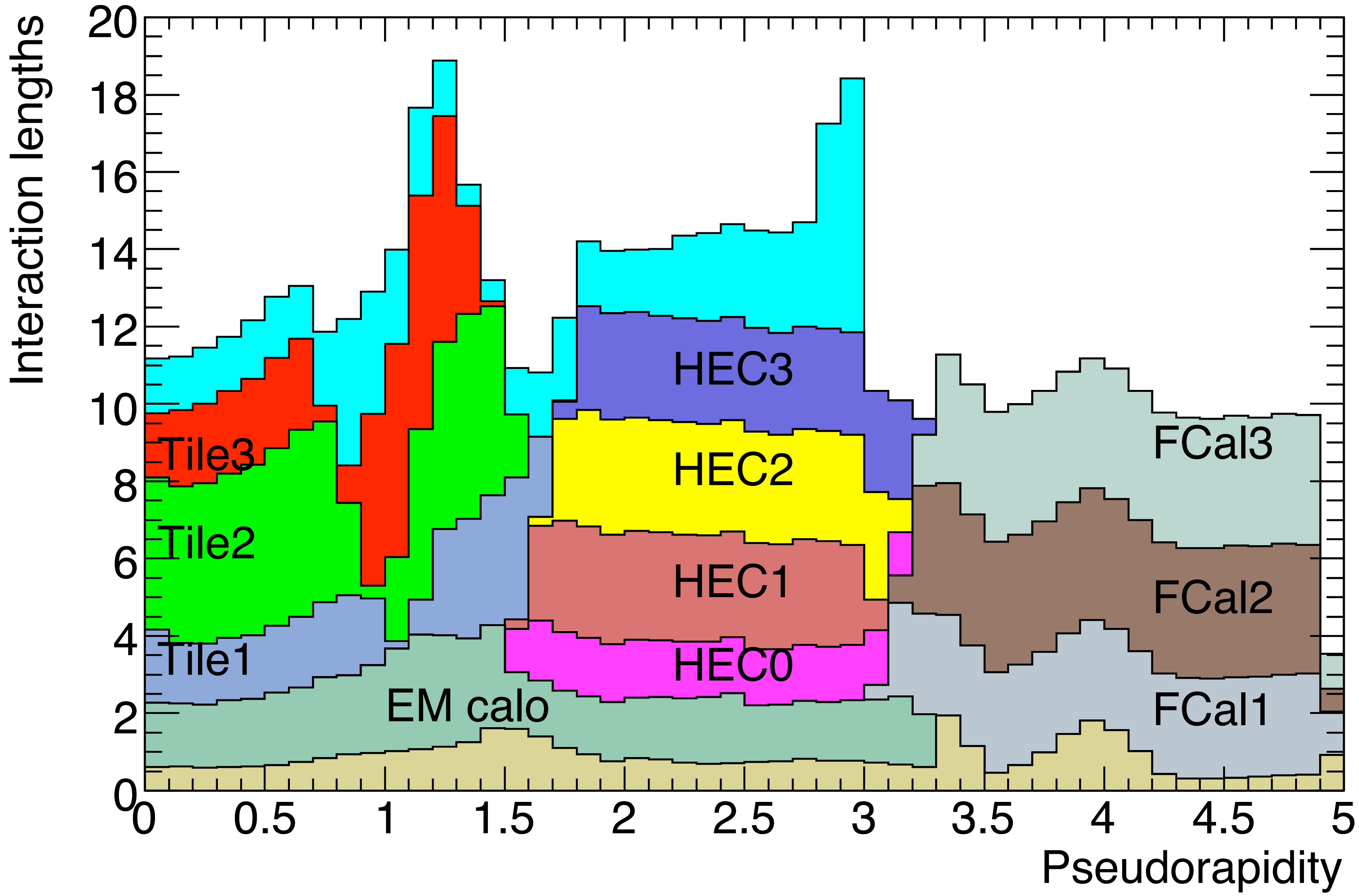
- Wrote a fast simulation of a perfect lead calorimeter that parameterizes the GEANT3 and 4 response to the interactions of "hadrons" with the calorimeters.* Nuclear interactions only.
- Example response for 300 GeV R-hadron:



*Kraan, hep-ph/0404001

Detector Geometry

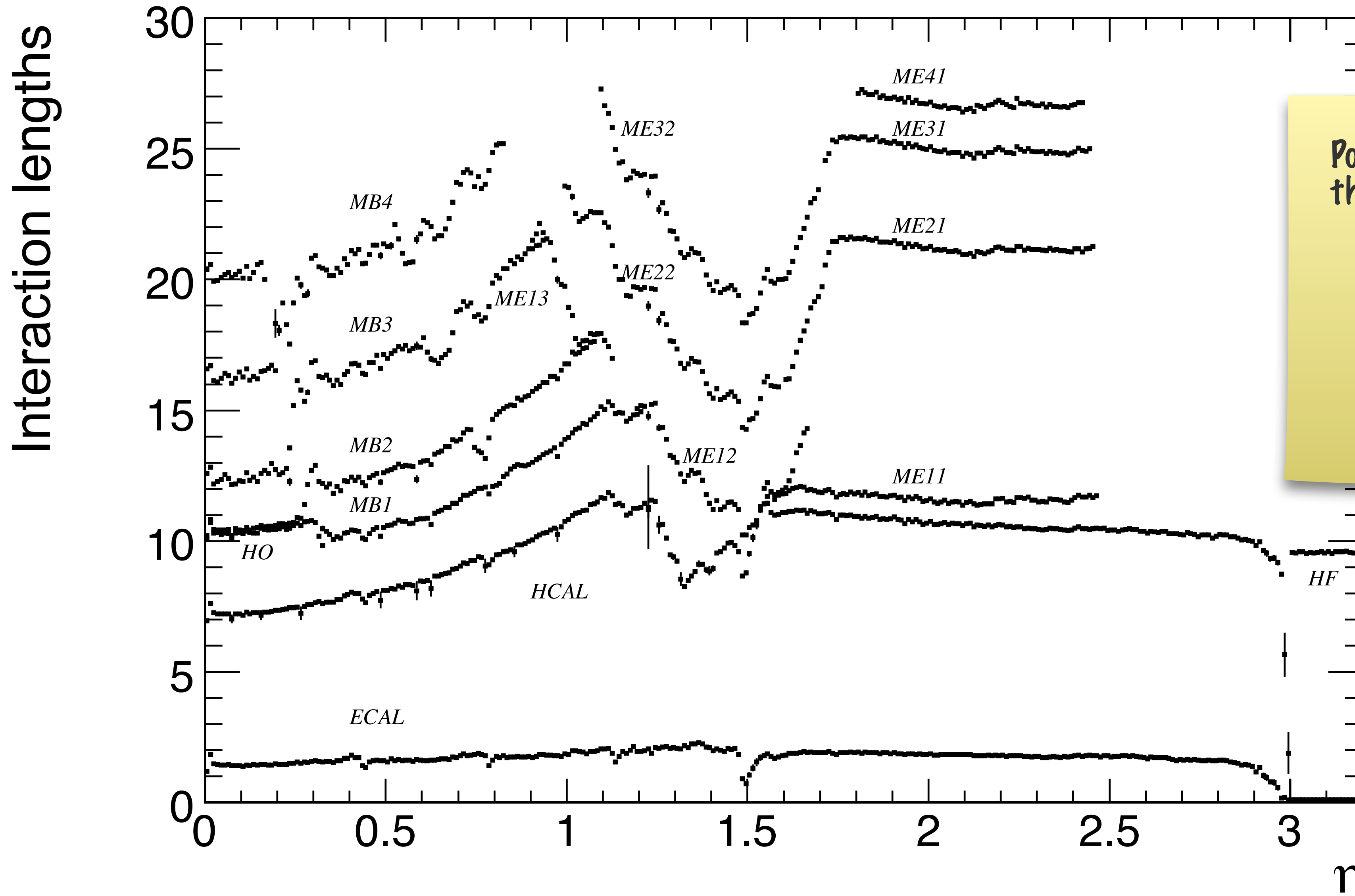
- ATLAS geometry in nuclear interaction lengths*



*See G. Aad, et al. JINST 3, S08003 (2008)

CMS Detector Geometry

- CMS geometry in nuclear interaction lengths**



Point out iron yokes in the muon chamber.

*See CMS TDR, Volume 1

Model Types

- Type II: DM symmetry associated with spontaneous symmetry breaking.

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    - Focus: Model that generates the DM stabilization symmetry by SSB thereby correlating the DM relic abundance to the weak scale.*

*D.W., arXiv:0907. 3146.

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- Type II: DM symmetry associated with spontaneous symmetry breaking.

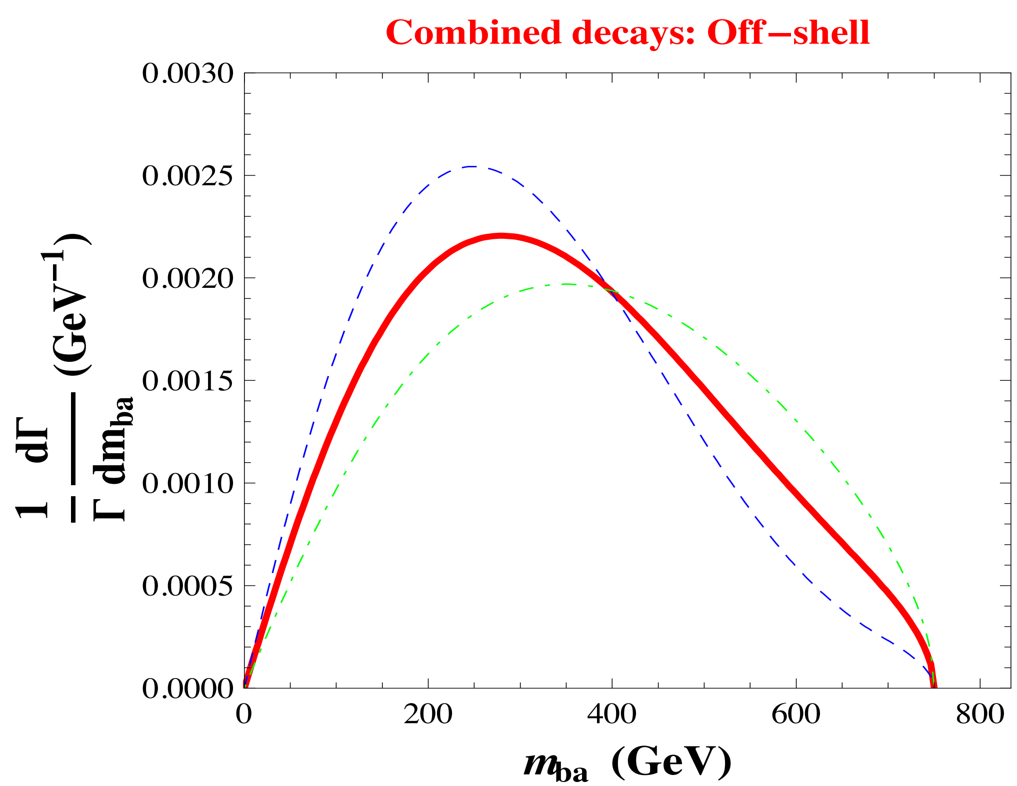
  - Focus: Model that generates the DM stabilization symmetry by SSB thereby correlating the DM relic abundance to the weak scale.*

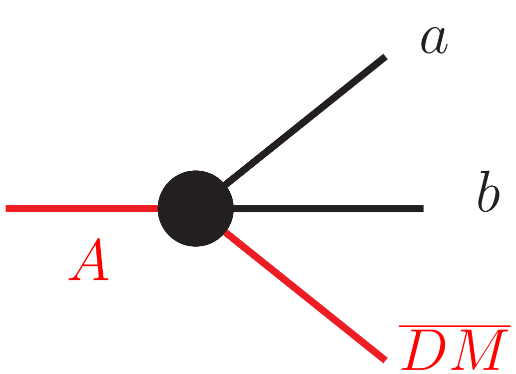
  - Also discuss how modifications to models which have non-trivial dark sectors can generate a signal.**

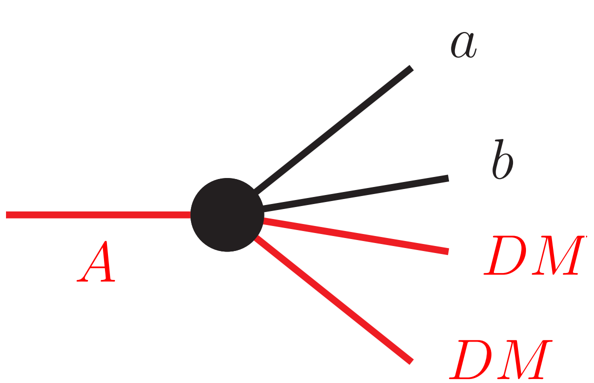
*D.W., arXiv:0907. 3146.
**Arkani-Hamed, Finkbeiner, Slatyer and Weiner, PRD 79, 015014 (2009),
Arkani-Hamed and Weiner, JHEP 0812, 104 (2008),
Pospelov, Ritz and Voloshin, PLB 662, 53 (2008).

Test

- Effect for large mass differences and small DM masses:







Test

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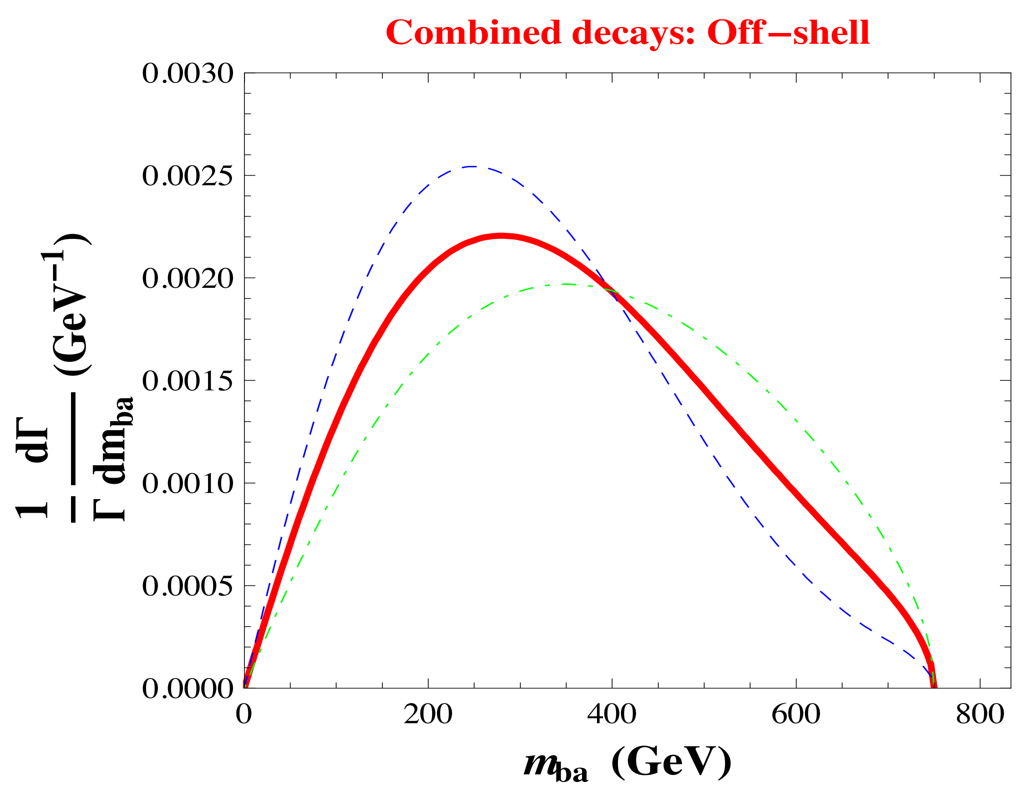

- 800 GeV mother and 50 GeV DM with no spin correlations.

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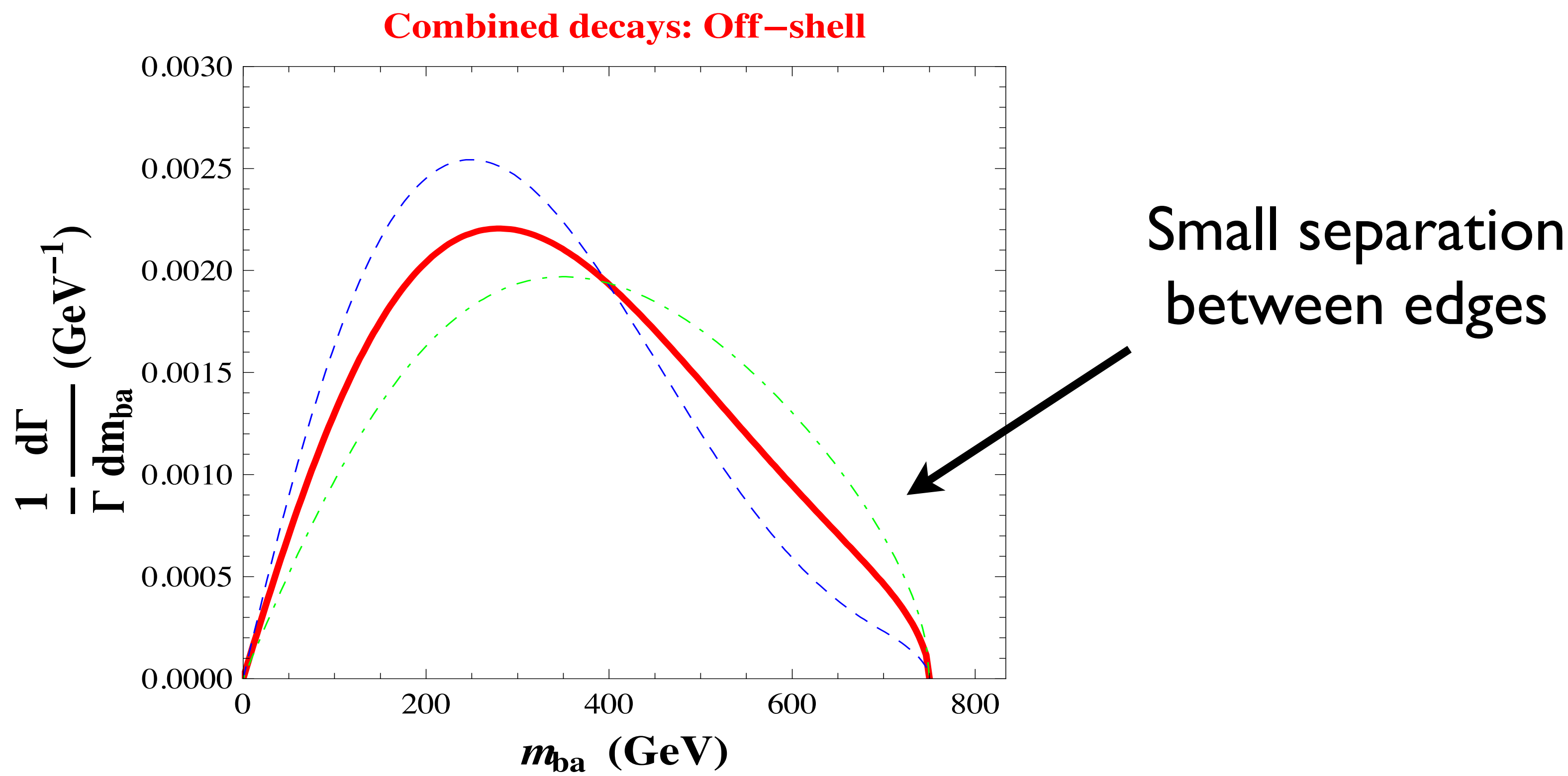

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- Type I: Warped Pati-Salam Unification models where the DM symmetry is a $\mathcal{Z}_3$.*

*Agashe and Servant, PRL 93, 231805 (2004); JCAP 0502, 002 (2005).

Model Types

- Type I: Warped Pati-Salam Unification models where the DM symmetry is a $\mathcal{Z}_3$.*

  - $\mathcal{Z}_3$ symmetry is generated from color and fractional baryon number of each particle.

$$\eta \to \exp\left[2\pi i\left(B - \frac{n_c - \bar{n}_c}{3}\right)\right]\eta.$$

*Agashe and Servant, PRL 93, 231805 (2004); JCAP 0502, 002 (2005).

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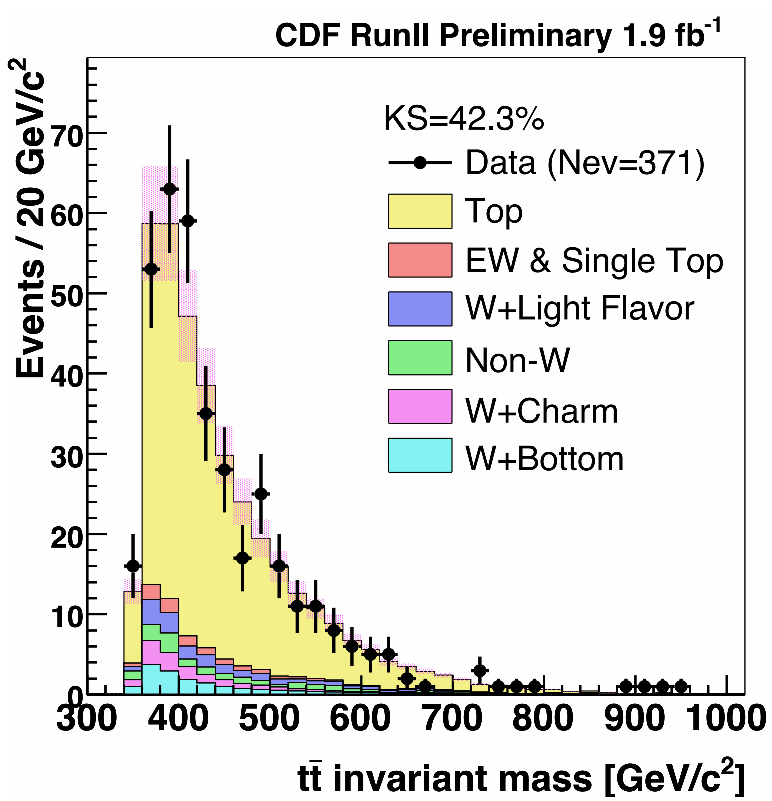
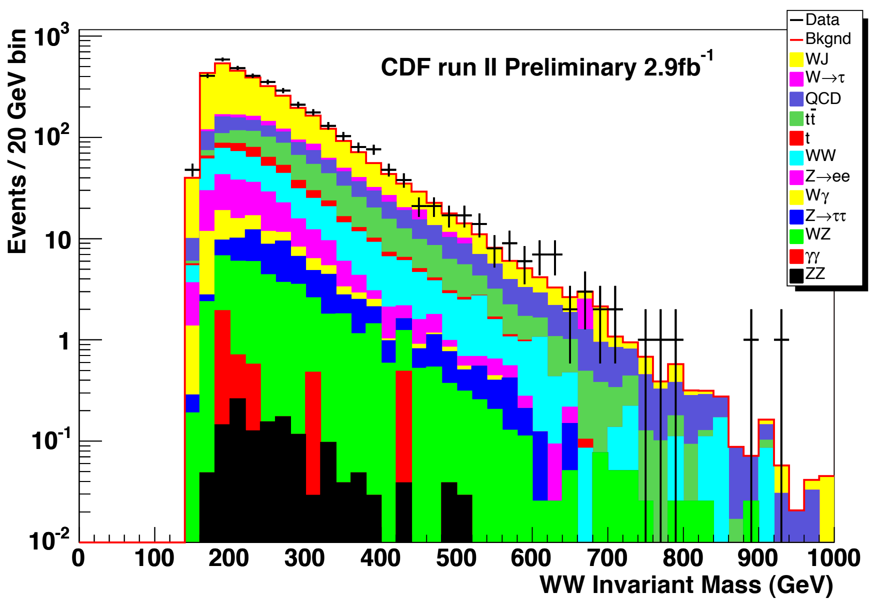
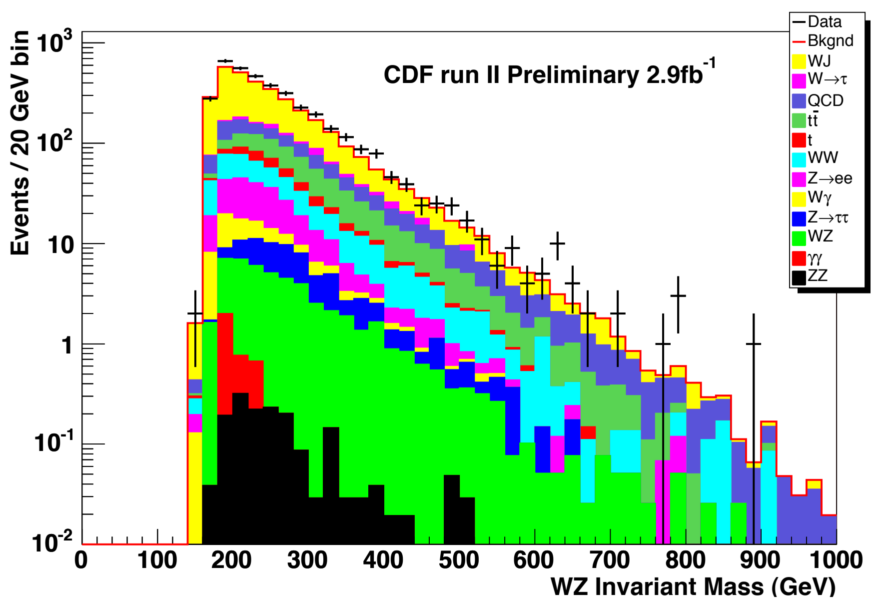
- TeVatron direct searches for parity even resonances exclude to about ~ 600 GeV. Examples:







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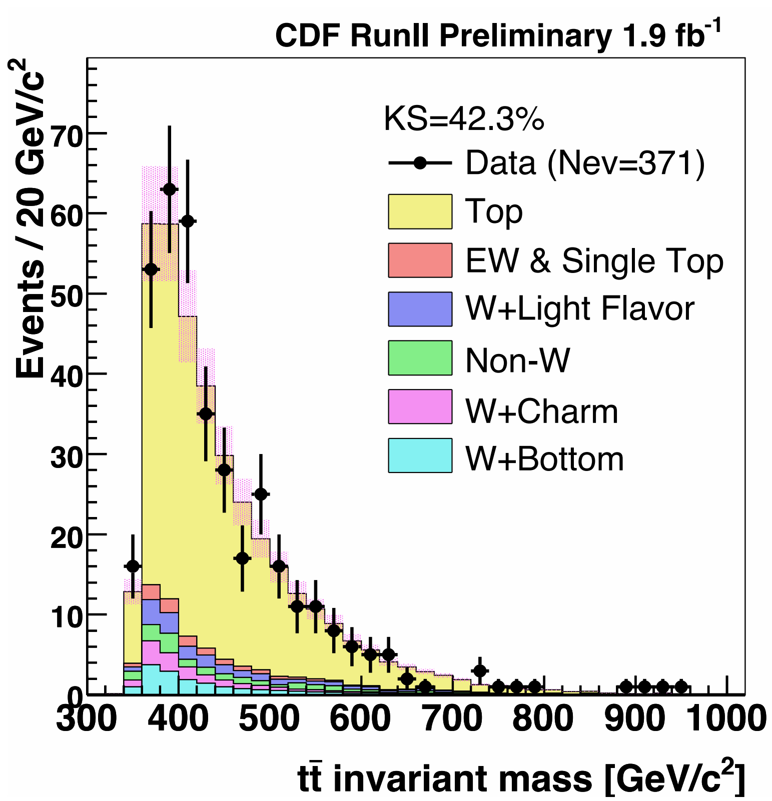
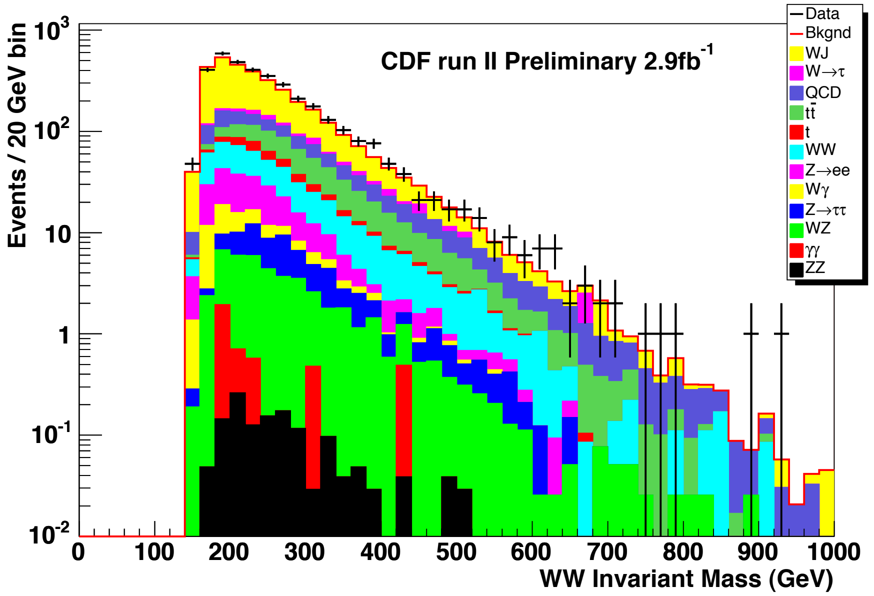
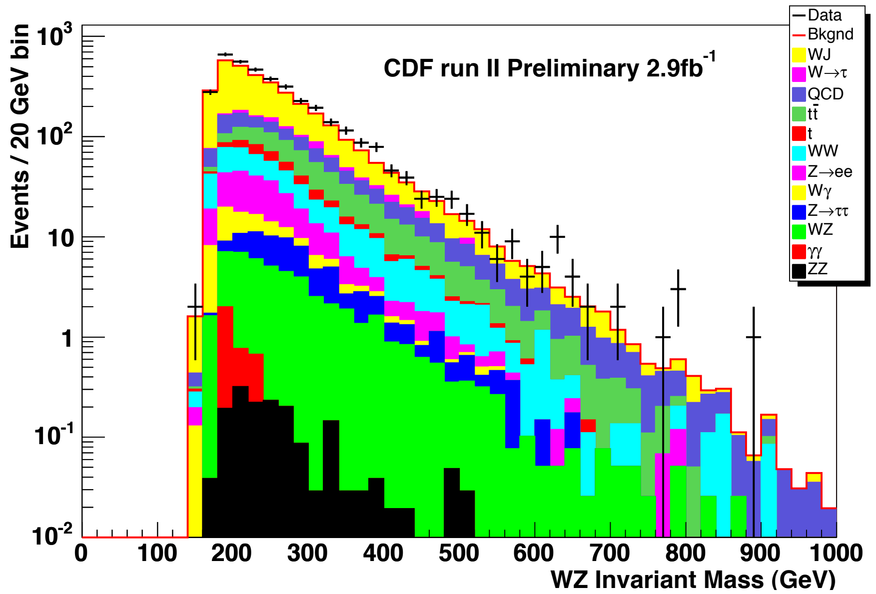
- TeVatron direct searches for parity even resonances exclude to about ~ 600 GeV. Examples:

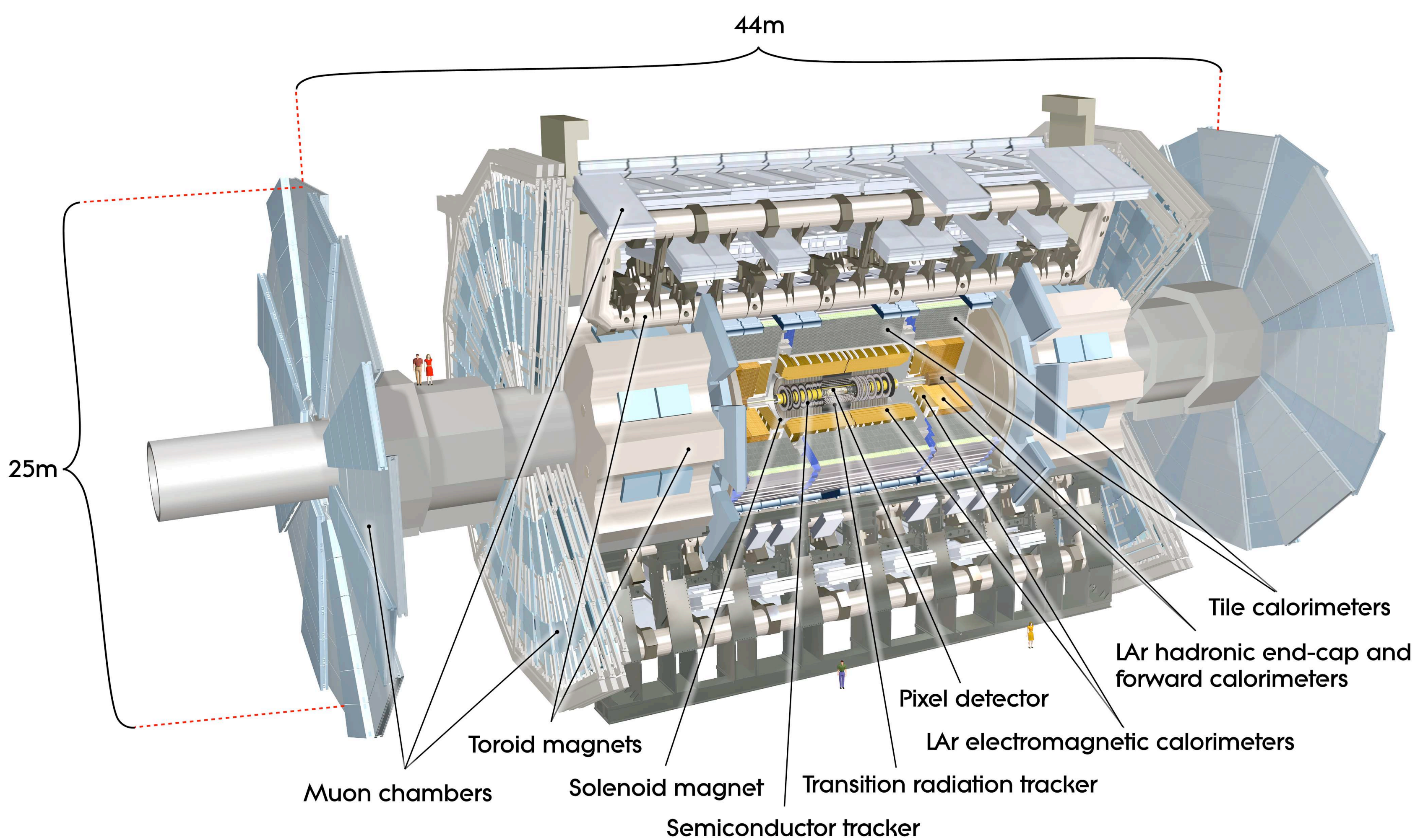






- Still not strong.

ATLAS Detector



Arguments Void?

- LHC discovers scalars that have a large enough branching fraction into the signal such that a SM decay is very rare and some symmetry is not responsible.

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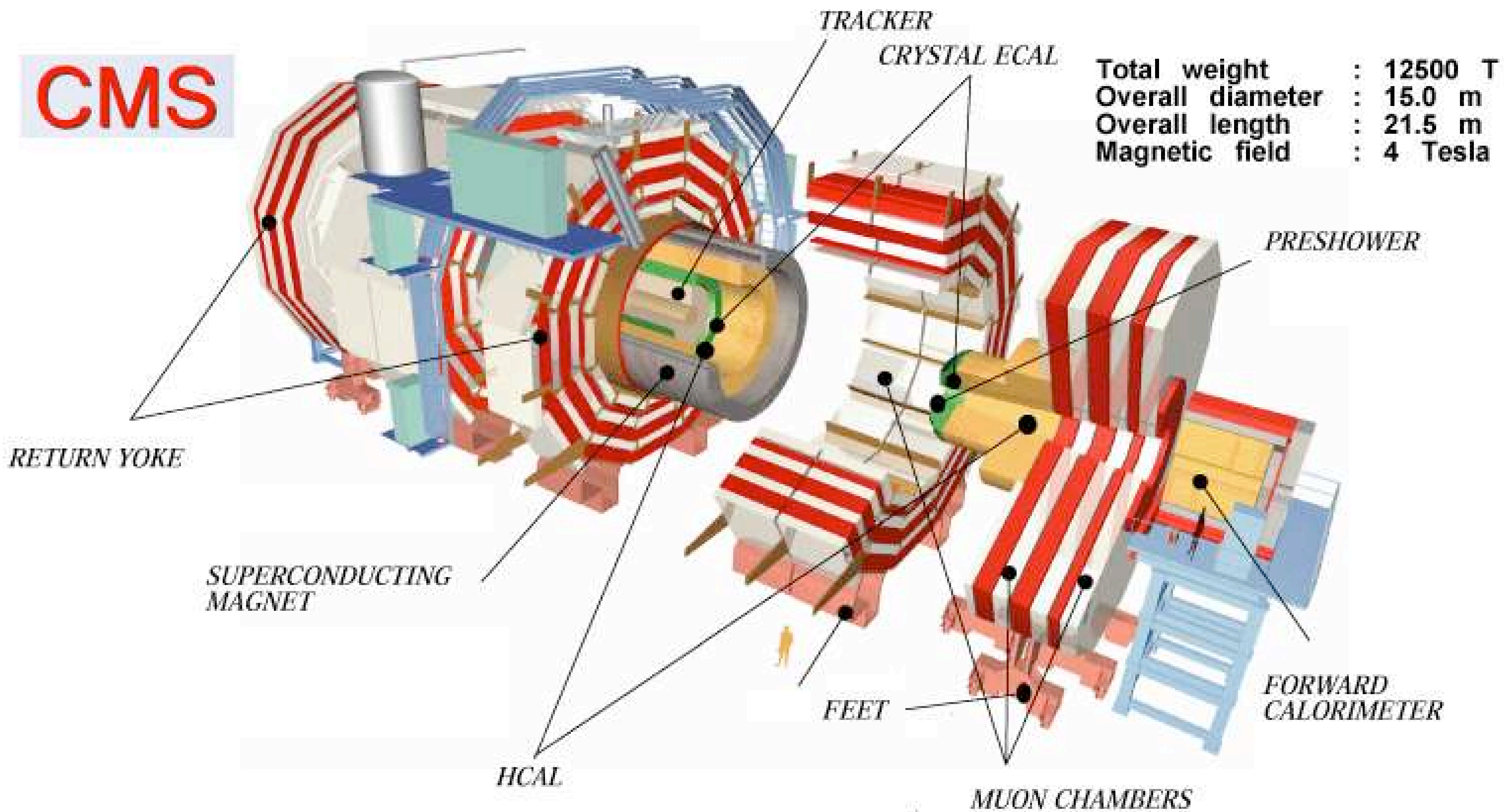
    - Anthropic arguments? Fine-tune couplings of scalar w/SM to generate 100% fraction to signal.

      Tantamount to adding a new symmetry to the DM. "Non-parity!"

CMS Detector



Assumptions

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- Long lived particles must decay via, e.g.,

$$\frac{1}{\Lambda^2} q\, q\, \psi\, \chi \qquad\qquad \frac{1}{\Lambda^2} l\, \nu\, \psi\, \chi$$

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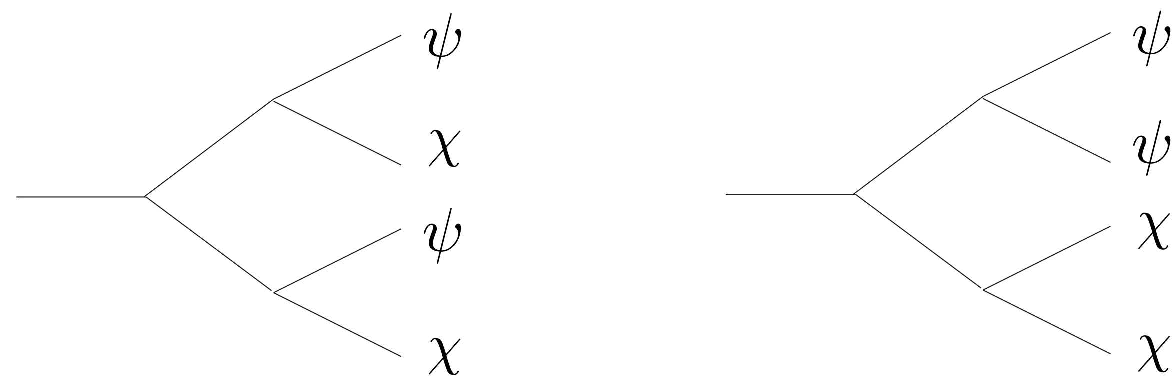
- Consequences:

  DM and meta-stable stabilization symmetries are correlated.

  Cannot randomly pick non-SM charges for ψ.

Remaining Diagrams Suppressed?



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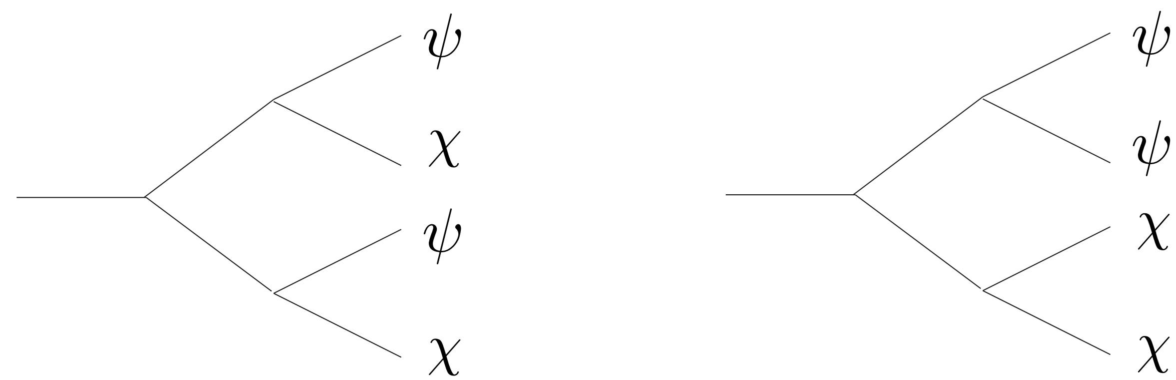

- Effective Field theory: New particles generally have O(1) couplings to SM.

  (remember new particles are parity even)

  - Result: Smaller branching fraction into signal.

Example Particle to Mediate Diagrams

- An Estimate: Virtual SM higgs particle. Decay rate

$$\Gamma_{h_0 \to \chi\chi \text{ scalar}} = \frac{\kappa_1^2 \, v_{ew}^2}{16 \pi m_{h_0}} \sqrt{1 - 4 m_\chi^2 / m_{h_0}^2}$$

$$\Gamma_{h_0 \to \chi\chi \text{ fermion}} = \frac{A \, \kappa_2^2 \, m_{h_0}}{32 \pi} \left(1 - 4 m_\chi^2 / m_{h_0}^2\right)^{3/2}$$

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- Similar statement for charged higgses.
- Stronger suppression statement.

Six Body States

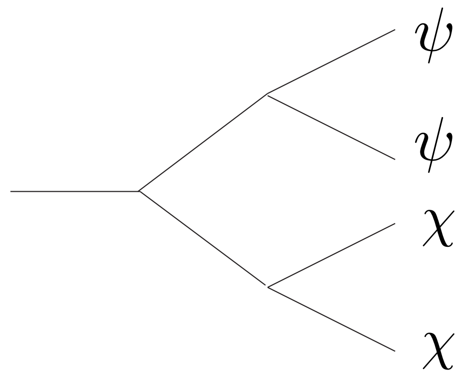
(that generate two meta-stable particles + missing energy)

- Diagrams overall suppressed compared to 2, 4 body diagrams.

- Same suppression/reconstruction conclusions as the arguments for four final body states.

Reconstructing Diagrams

Similar arguments
for this diagram



Reconstruct in analogy to ZZ production.

Meta-Stable Quarks

- Analogous charge flipping for R-hadrons interacting with the detector*

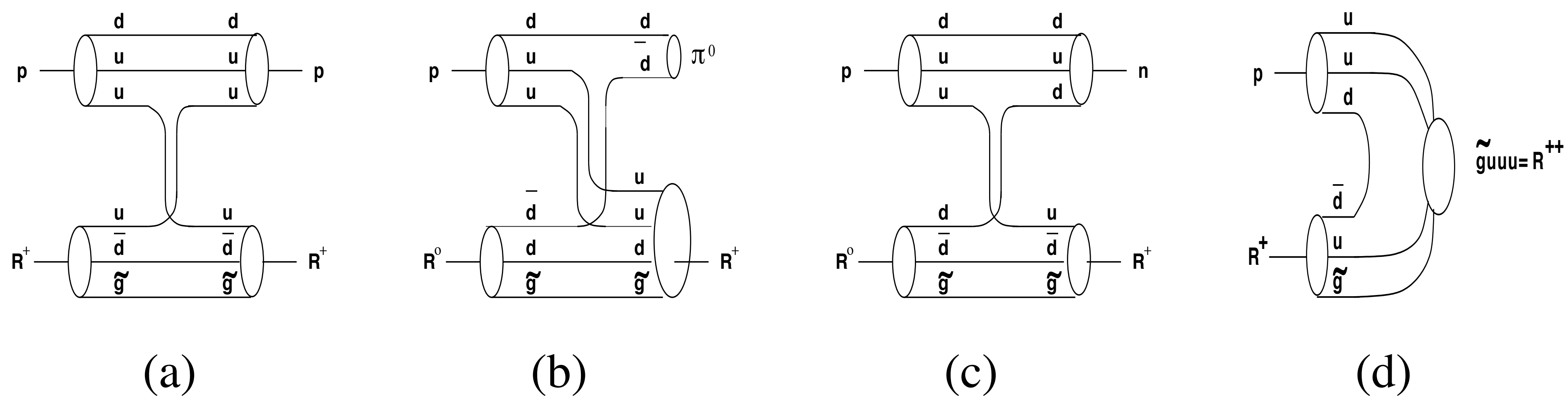


Fig. 13. R-hadron-proton scattering processes. (a) Elastic scattering, (b) Inelastic scattering leading to baryon and charge exchange, (c) Inelastic scattering leading to charge exchange, (d) Resonance formation.

*From review, Fairbairn, et al. hep-ph/0611040

Meta-Stable Particles Redux

- Particles are cleanly tagged at the LHC
  - S/B ~ O(100) for 1 fb^{-1} for ATLAS and CMS.*
- Meta-stable quarks "hadronize" into "mesons" and "baryons."
- "Mesons" and "baryons" charge flip, loose energy and even stop in the detector by exchanging valence quarks with the calorimeter.

* G. Aad, et al. [The ATLAS Collaboration], arXiv:0901.0512,
A. Rizzi, et al. [The CMS Collaboration], CMS-AN-2007/049.

Meta-Stable Velocities

- The "hadrons" and "leptons" look like slow, heavy "muons" in the muon detector.

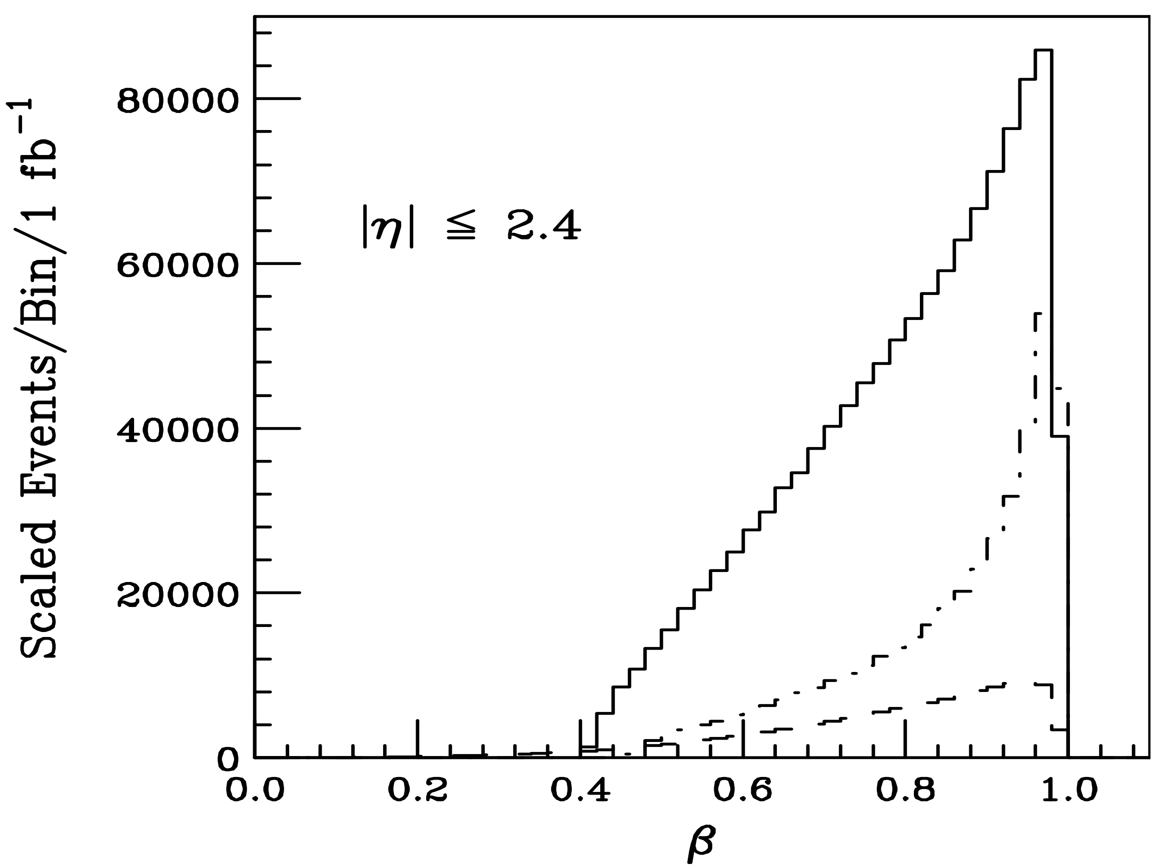


FIG. 2: Scaled events versus velocity for a 300 GeV N-hadron with (dashed) and without (solid) emission of the dark gauge boson. 200 GeV stable lepton is dot-dashed. The histograms are scaled by 20, 1 and 200, respectively.

Time of Flight Issues

- Trigger on "heavy muons" which are out of time with rest of the relativistic event.
- "Muons" that are too slow are problematic. Can be reconstructed with the wrong event.

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- "Muons" that are too slow are problematic. Can be reconstructed with the wrong event.
    - LHC proton beams are collimated in bunches separated nominally by 25 nanoseconds.
    - A problem for ATLAS because of it's size. Up to three events are in the detector at one time.

Fast Detector Simulation

- To do the analysis wrote a fast simulation to parametrize the detector effects of Geant 3 and 4.

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- Details are not in the mainstream of this talk . . .